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IOT*(AMBISENSE) – SMART ENVIRONMENT MONITORING USING LORA

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A Dissertation presented in partial fulfillment of the Requirements for the Degree of Master in Telecommunications and Computer Engineering

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Resumo

Nesta dissertação de mestrado, IoT * (AmbiSense), é apresentado um sistema IoT desenvolvido como uma solução para Gestão de Edifícios e Energia recorrendo a ferramentas de visualização para identificar heurísticas e criar poupanças automáticas. Os protótipos desenvolvidos comunicam utilizando LoRa, e são compostos por um conjunto de sensores ligados a um microcontrolador alimentado por bateria. Os sensores adquirem dados como temperatura, humidade, luminosidade, qualidade do ar e movimento.

Para edifícios de pequena e média dimensão onde a gestão do sistema é possível, um *dashboard* fornece *templates* de visualização com dados em tempo real, permitindo extrair heurísticas, que introduzem poupanças através de um conjunto de ações predefinidas ou intervenção manual. O sistema LoBEMS (LoRa Building and Energy Management System), foi validado numa escola local durante um período de três anos. A avaliação do sistema resultou numa poupança de energia de 20% e uma melhoria significativa da qualidade do ambiente e conforto no interior da escola.

Para edifícios de maior dimensão onde a gestão do sistema não é possível, criámos uma ferramenta de visualização 3D, que apresenta os dados e alertas do sistema, num modelo interativo do edifício. Este cenário foi validado no campus do ISCTE-IUL, onde foi necessária a interação da Comunidade para obter poupanças. Foi nos também solicitada uma validação do sistema no centro de dados da Universidade, onde os *templates* do sistema foram utilizados para detetar anomalias e sugerir alterações.

A flexibilidade do sistema permite a sua implementação em qualquer edifício, sem exigir um grande investimento ou implementações complexas.

Palavras-chave: Internet das Coisas, Sustentabilidade, Poupanças Energéticas, Gestão de Edifícios, LoRa, *Templates*, Sensores

Abstract

In this work, IoT* (AmbiSense), we present our developed IoT system as a solution for Building and Energy Management using visualization tools to identify heuristics and create automatic savings. Our developed prototypes communicate using LoRa, one of the latest IoT technologies, and are composed of a set of battery-operated sensors tied to a System on Chip. These sensors acquire environmental data such as temperature, humidity, luminosity, air quality, and also motion.

For small to medium-size buildings where system management is possible, a multiplatform dashboard provides visualization templates with real-time data, allowing to identify patterns and extract heuristics that lead to savings using a set of pre-defined actions or manual intervention. LoBEMS (LoRa Building and Energy Management System), was validated in a kindergarten school during a three-year period. As an outcome, the evaluation of the proposed platform resulted in a 20% energy saving and a major improvement of the environment quality and comfort inside the school.

For larger buildings where system management is not possible, we created a 3D visualization tool, that presents the system collected data and warnings in an interactive model of the building. This scenario was validated at ISCTE-IUL University Campus, where it was necessary to introduce the community interaction to achieve savings.

As a requested application case, our system was also validated at the University Data Center, where the system templates were used to detect anomalies and suggest changes.

Our flexible system approach can easily be deployed to any building facility without requiring large investments or complex system deployments.

Keywords: Internet of Things, Sustainability, Energy Savings, Building Management, LoRa, Templates, Sensors

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Contents

List of Tables

List of Figures

Nomenclature

A/C	Air Conditioning
ABP	Activation by Personalization
AC/DC	Alternate Current/Direct Current
API	Application Programming Interfaces
BEMS	Building and Energy Management System
BIM	Building Information Model
BMS	Building Management System
bps/kbps	bits per second/kilobits per second
CT	Current Transformer
DB	Database
EMS	Energy Management System
GPIO	General Purpose Input/Output
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HTTP	Hypertext Transfer Protocol
HVAC	Heating, Ventilation, & Air Conditioning
IDE	Integrated Development Environment
IFTTT	If This Than That
IoT	Internet of Things
IP	Internet Protocol
IR	Infra-Red
ISN bands	Industrial, Scientific and Medical bands
IT	Information Technology
LED	Light Emitting Diode
LoBEMS	LoRa Building and Energy Management System
LoRa	Long Range
LoRaWAN	LoRa Wide Area Networks
LPWAN	Low Power Wide Area Networks
LTE	Long Term Evolution
MDA	Model-Driven Approach

MQTT	Message Queuing Telemetry Transport
NB	Narrow Band
OpenADR	Open Automated Demand Response
OTAA	Over The Air Activation
PIR	Passive Infrared
PWM	Pulse Width Modulation
RSSI	Received Signal Strength Indicator
SNR	Signal-to-Noise Ratio
TTN	The Thinks Network
UI	User Interface
WSN	Wide Sensor Network

Chapter 1 - Introduction

1.1. Motivation

During the 20th century, the third industrial revolution determined the beginning of a new era, the digital age, and the incorporation of high technology into all branches of science, industry, public services and, in general, people's daily life.

The fourth industrial revolution begins "today", the search for automation technologies, data manipulation, human-machine interaction, Internet of Things, has increased exponentially, and because of that, the applications for them too. In a world where everything can be connected to the Internet, simple tasks such as turning off a light or driving from one point to another, are being done without complete or partial human intervention. This revolution aims to introduce a certain autonomy into machines, to optimize their operation, reduce human interference, and ultimately improve the quality of life.

With the increase of technologies in cities of the future, the volume of stored data that support their operation also increases. Information processing, storage, and protection are extremely important since any losses can lead to serious economic, security or privacy threats.

Since the first industrial revolution, the world's energy consumption has increased exponentially. During the 20th century, the world population consumed 1.2 million kWh per capita. Nowadays, this value has more than tripled accordingly to [1].

Fossil fuels were always essential for energy production, representing still 80 % of the current consumption worldwide [1] and one of the main responsible for CO_2 emissions within the energy sector.

Accordingly to [2], since the 19th-century CO_2 concentration on the earth's atmosphere has increased by 40%, and 68% is due to energy production. Despite advancements in renewable energies, the increasing energy demand to satisfy the needs of all electrical appliances, and the infrastructure that is going to support smart is much faster than renewable energies development and deployment.

To prevent a climate/energy crisis, it is essential to design and create the most efficient low-cost technologies, as well as reduce current energy consumptions and CO_2 emissions at domestic, public and industrial levels.

Dated from December 2015, the Paris Agreement was created as an international effort to reduce worldwide CO2 emissions and sustain a maximum temperature rise of 1.5ºC this century, by establishing a reduction target for each country, member of the International Energy Agency. By December 2018, Russia, Saudi Arabia, Turkey, Ukraine and the United States of America efforts were rated critically insufficient, aiming for a global temperature rise of 4ºC, 2.6 times the Paris Agreement limit, and only Morocco and The Gambia efforts were compatible with the established limit. No country is aiming to reach a lower limit than the 1.5ºC of the agreement until 2030 [3], as illustrated in Figure 1.

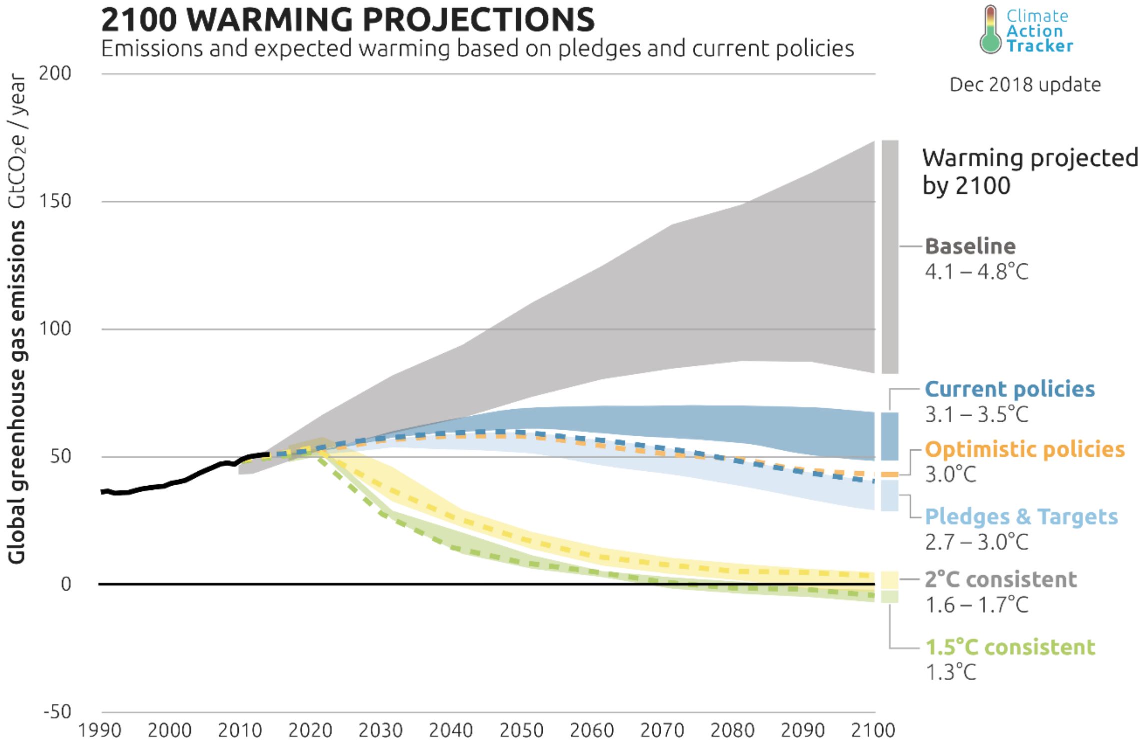


Figure 1- Global warming predictions based on historical data, current policies, defined targets by the Paris Agreement, and best /worst-case scenario. Retrieved from [3]

1.2. Context

In the digital era, the Internet of Things has been growing, and new technologies are being developed to provide, shortly, the essential tools for the creation and management of intelligent cities, based on a virtual ecosystem of thousands of sensors with specific functions.

A network of IoT sensors spread across entire cities requires long range connection capabilities, and because of that, it was necessary to develop new communication protocols, taking into account existing technologies and their limitations.

LoRa or Long Range was created for this type of sensor network. It uses a free band of the frequency radio specter to allow the communication between sensors, called nodes, and the access points connected to the Internet, called Gateways, through long distances. Operating at 868 MHz in Europe and 915 MHz in North America, due to 125kHz to 500kHz bandwidth being very low, this technology only allows the transmission of a very low bit rate, however, a study has determined a reach of approximately 18.5 Km at rural regions and 6.5km in urban areas [4].

The bit rate limitation is not relevant when we refer to IoT devices such as sensors that gather information from the environment and transmit it to a central processing unit without the requirement of frequent or real-time transmissions.

Usually, only people qualified with software skills can use or develop complex Building Management Systems capable of interacting with connected devices on a specific building and introduce savings. It is necessary to take these essential tools to the consumer itself, in a way that a homeowner or a business manager can easily configure and adapt the system to their own needs without advance knowledge.

1.3. Objectives

This work objective is to develop a low-cost and low power IoT System for Building and Energy management, able to provide real-time context information and promote energy savings, using a custom template-based dashboard solution, and a 3D visualization tool.

It was necessary to develop hardware, integrate LoRa, (an Internet of Things dedicated communication technology), into the system, and develop visualization tools required to present results to:

- 〉 Small/Medium facilities where dedicated system management is possible by managers intervention;
- 〉 Large buildings, such as a University Campus, where the University community can easily interact with the system and create savings using 3D models of the building, replacing dedicated system management;

After deploying and analyzing the collected data from an application case oriented for small/Medium facilities, with dedicated system management, and an application case oriented for large buildings, without dedicated system management, we can answer a few questions:

- In the application case where the system is fully implemented with system management, there are some essential metrics we can obtain, such as building energy usage and how the person in charge uses the system.
  - In which way can our Building and Energy Management System, or BEMS, increase the environmental quality?
  - Are the initial system costs and maintenance costs justifiable by the savings inherited by its good use?
  - How can we assure the accuracy and precision of the collected data?
  - Can we identify patterns and wastes of energy from the template-based analytics dashboard?
  - Do managers believe this system will be an advantage for their business?
- By using a 3D model of ISCTE-IUL University’s building, we expect to immerse the university community into our system and create a starting point for changing user behaviors and create savings.
  - Is it practical to introduce architectural tools into our developed system, using Unity?
  - Is this solution capable of presenting understandable and direct visual data from the collected information?
  - Do people believe our system can improve the University environment quality?

As a proposed application case by the ISCTE-IUL University, our system was also tested in ISCTE-IUL data center, to detect environment anomalies and study temperature and humidity gradients inside the room.

After applying our templates and visualization tools, we can evaluate our system versatility and scalability, and finally understand how it performed in each case, considering the objectives and obtained results.

1.4. Structure of the Thesis

In the next Chapter 2, we reviewed existing and previously studied systems, related to each of our application cases:

- For the first application case at a local Kindergarten, we did a systematic survey to understand current market solutions for Building and Energy Management Systems;
- For the 3D BIM model, we studied ongoing work being developed with this tool and how it can be applied in an educational environment;
- For the proposed application case at the University Data Center, we studied the importance of such buildings, their main problems, possible solutions, and how existing systems work.

In Chapter 3, we introduce the system's main requirements, and for each layer module, we describe how we implemented and developed our solution.

- At the Device layer, we present our developed sensor box prototype and the steps we took till the final product, from materials choosing to hardware evaluation and configuration.
- On the communication layer, we explain how the LoRa network works, is advantages and disadvantages, and how we introduced it into our system.
- The application layer is based on Node-Red software, which we used to develop our templates, and the BIM model, also described in this chapter.

Chapter 4 is where each application case is thoroughly described. For each application case, we characterized the location, defined objectives, created a deployment map, and chose the templates required for the application. Finally, we present the obtained results.

To conclude, in Chapter 5, we discuss the project results, featured published papers, and future work on the system.

Chapter 2 - State of the Art

2.1. Building and Energy Management Systems

Energy management in the context of the building is a similar system to our proposal, but traditionally these Energy Management Systems (EMS) or Building Management Systems (BMS) are based on Smart devices, Wireless Sensor Networks (WSN), and a centralized platform for data presentation and management. Examples of these systems are in references [5]–[8], including implementations of Energy Management Systems with Wireless Sensor Networks that use ZigBee Module for communication with sensor nodes. Other works have been extended to longer ranges in the IoT paradigm utilizing the GSM/GPRS (Global System for Mobile/General Packet Radio Service) networks to remotely control the end-devices [9], [10], but these networks have the problem of power consumption and range. We consider this a drawback for battery-powered sensors that have the advantage of avoiding installation cables. Other studies applied scheduling approaches to optimize HVAC energy consumption [11]–[13]. In reference [14], a home controller system integrated with sensor devices is responsible for aggregated energy reporting of all devices to homeowners. In reference [15], authors create an IoT based Direct Current (DC) powered home to develop a DC distribution system encompassing all residential DC-based loads that interact with each other. However, the lack of standardized protocols and regulations were the main challenges in considering intelligent DC powered homes as a suitable replacement to Alternated Current (AC) power systems. Challenges could be overcome with IoT that will provide an integrated platform for DC powered technologies with inefficient energy distribution. Using smart meter data, this EMS can monitor and provide real-time information on home energy consumption along with online access to the device's status, thus allowing remote control of devices by customers. The proposed design is based on standard Hypertext Transfer Protocol (HTTP) protocol and does not provide support for lighter-weight communication protocol like Message Queuing Telemetry Transport (MQTT) which is essential to scale up the system in order to accommodate multiple residential areas. In reference [16], a residential gateway controller was developed with a central management system that generated an operation plan for all the connected nodes in a home network depending on weather conditions.

Additionally, the researchers in reference [17] propose a cost modeling scheme for an optimization-based energy management model that aims at reducing the energy expenses of consumers. Another study found that a Home energy management system can reduce electricity consumption by 15%, potentially with acceptable discomfort [18], [19].

In [4] the authors compiled several electricity savings studies to determine what type of feedback an energy management system should have to optimize the results and concluded that Real-time feedback systems are the most efficient, rather than estimated or periodical feedback reports.

In Table 1, we summarized alternative Building and Energy Management Systems, together with our proposal, taking into account the following data facts: 1) The domain of application reported in work; 2) If it is associated with data collection in a real implementation case; 3) If a data set was provided for scientific usage and the number of years of this dataset; 4) The data collected from implemented sensors divided into utilities (electricity, water, and gas) and environment data (temperature/humidity, Gases-CO/NO2/O3/SO2, this is a sensor layer description; 5) Communication layer description with the communication protocol used; 6) Application layer, associated with IoT Platform; 7) Information related to energy savings and related topics divided by automatic actions and Human actions that can be divided by in the following interactive features: i) real time information sensor data available on mobile devices; ii) user behavior modeling processes through any interactive applied process; 8) if the system has implemented any prediction process using collected data; and 9) If the system development is a commercial type or open source based.

Table 1 - Building and Energy Management Systems comparison table

Reference Case	**Application Domain**	**Dataset size (years)**	**Utilities**			**Environment**		**Com. Protocols**	**IoT Platform**	**User Feedback**	**Realtime Measure**	**Realtime Savings**	**User Behavior Modeling**	**Predictive Analytics**	**Commercial/ Open Source**
			Electricity	**Water**	**Natural Gas**	**Temperature/ Humidity/Light/ Motion**	**Gases C0/NO2/ 03/SO2**								
Our System	**Multiple**	**Yes**	**Yes**	**No**	**No**	**T/H/L/M**	**Yes**	**LoRa**	**Local OS**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Open Source**
[5]	Home	No	Yes	No	No	No	No	ZigBee	Cloud	Yes	Yes	No	Yes	No	NA
[7]	Home	No	Yes	No	No	T	No	ZigBee	Local OS	No	Yes	Yes	No	No	NA
[8]	Home	Yes	Yes	No	No	T/H/L/M	Yes	ZigBee	Cloud	No	Yes	Yes	No	Yes	Commercial
[9]	Factory	No	Yes	No	No	No	No	WiFi	Cloud	Yes	Yes	No	No	No	Commercial
[10]	Home	No	Yes	No	No	T/M	Yes	ZigBee	Local OS	Yes	Yes	No	Yes	No	Commercial
[11]	Office	Yes	Yes	No	No	T	No	WiFi	Local OS	Yes	Yes	Yes	No	Yes	Opensource
[12]	Subway	No	Yes	No	No	T	No	NA	NA	NA	Yes	Yes	No	Yes	Commercial
[13]	Office	Yes	No	No	No	T/H/L	Yes	WiFi	Cloud	Yes	Yes	No	Yes	No	NA
[14]	Home	No	Yes	No	No	T/H/L	No	WiFi	Cloud	Yes	Yes	No	Yes	No	Commercial
[16]	Home	Yes	Yes	No	No	T	No	WiFi	Local OS	Yes	Yes	No	No	No	Commercial
[17]	Home	No	Yes	No	No	No	No	ZigBee	Local OS	No	Yes	No	No	No	NA
[19]	Home	Yes	Yes	No	No	No	No	NA	Local OS	No	No	No	Yes	No	NA

OS: Open Source; NA: Not Available; Environment measurements (T/H/L/M): Temperature, Humidity, luminosity, motion; Com: Communication.

Most works related to BEMS are based on simulations and test datasets. Our system is fully implemented and running with real-time data on a 24/7 basis. It also differentiates itself from other systems due to the amount of provided features such as automated savings and the impact caused on user behavior once they begin to interact with it.

The technology our system uses, also allows easy deployment and extended coverage from the gateway, on the other hand, ZigBee and WiFi, usually used by other BEMS, rely on proximity to the gateway.

Feedback on energy consumption at home potentially results in up to 15% in energy savings [20]. This is a basic approach to providing information about energy consumption in a certain period. Past studies show that energy savings typically fall in the region of 5%–20% [21]. User behavior is also an important factor in this saving process of consumed energy [22]. Report information on users shows that energy levels have the potential to be reduced with little or no impact on household well-being. Also, user reports about consumption lead them to engage in energy-saving behaviors.

Eco-feedback applications are usually based on the assumption that individuals lack awareness and understanding of how their everyday activities affect the environment [23]. Therefore, eco-feedback applications not only present the amount of consumed or conserved energy as feedback, but also have the potential to point out the consequences of this consumption on the environment. Further, eco-feedback applications can provide comparisons between a user’s consumption vis-à-vis that of their neighbors and friends, as well as disclose devices or activities that are energy-intensive. The manner in which individuals will react to the information content of the feedback provided is largely dependent on their motivation to conserve energy. A recent survey [24] performs a systematic overview of current approaches in this topic divided into conceptual and experimental approaches. Taking into account the experimental studies, most of these studies focus on exploring and identifying challenges in user behavior modification towards saving actions. Our approach was able to perform an automation process of saving actions, taking into account locally collected data. The collected data can be manipulated in pre-defined templates (this can be used in any system) into reports that allow users to extract heuristics. Most important savings are achieved at the main application case, the kindergarten school, by controlling the heating/cooling system working times, but we can also apply saving rules to lights and other electrical appliances.

These working rules can be programmed to work automatic using infrared remote commands on air conditioners or even with the application of an openADR standard [25], [26]. This protocol allows the remote turn on/off and any appliance that has this standard implemented. Also, these heuristics can be applied during any system phase, since they do not require any previous data.

2.2. Building Information Modeling

During the time of the year when temperatures reach extreme values below or above the level of comfort, HVAC (heating, ventilation and air conditioning) systems represent a large part of buildings' energy consumption, being directly proportional to its size. More than the HVAC capacity to produce cold/heat, a relevant factor to the temperature balance inside a building is the ability to retain heat. Resulting from the materials used in construction, the quality of building insulation can be a substantial problem for both the consumption of HVAC systems, and comfort inside the structure.

Building Information Modeling, or BIM, “a modeling technology and associated set of processes to produce, communicate and analyze building models, where building models are digital objects associated with computable graphics, parametric rules, and data attributes” [27]. Through this type of computing platform, it is possible to analyze the ability of the building to retain heat, as well as simulate changes in real-time, for example, considering outside temperature or heat sources.

In Figure 2, it is possible to determine where a building loses more heat by using BIM technology together with pre-existing information about the building structure and materials [28].

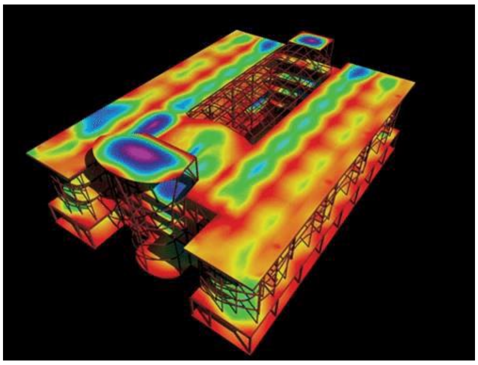


Figure 2- Example of a thermic analysis using BIM tools. Retrieved from [34]

It is also a method of renovating existing buildings, with the required tools to identify problem areas and to better understand the dynamics of the, and its materials. EnergyPlus platform (BIM-based) tool was used to study the energy consumption in a House not isolated before and after a renovation, considering changes individually and together in Belgrade in Serbia[29].

At [30], a BIM model, which can be seen in the next Figure 3, was initially developed to improve and update ISCTE-IUL University events management and as a visual maintenance tool to keep track of equipment malfunctions/repairs and other systems in real-time. According to the authors, other applications could be related to "institutional communication, 2D drawings, indoor navigation or virtual and augmented reality systems".

Figure 3- ISCTE-IUL University Campus, BIM Model at the modeling phase. Retrieved from [36]

In this model, which is in continual development, it is possible to add any object and provide or remove data from it, being a qualified tool for the analysis of temperature gradients determined by our developed sensors and how temperature relates with the building itself, its materials and content [30].

Besides the author's goals, Building Information Modeling could also be used for:

- Synchronization of contained spaces information with various systems such as occupation (staff, teaching and research units, study areas, restaurants), features of spaces (such as lighting type, capacity, comfort, ventilation);

- The compilation, storage, and processing of information relating to the most appropriate equipment, not only concerning geometric information (characteristics and location) but also features like manufacture, supplier, user manuals instructions, warranties, maintenance dates, etc.
- Generation of written reports and graphs about the information contained in the model, satisfying the regular requirements of various units, but also to support decision making and strategic planning.

2.3. Data Center monitoring

A data center is a space where computer systems, essential to a given company or organization regular operation, are located, together with redundancy systems capable of mitigating losses due to computational failures. These systems are usually telecommunications, centralized storage of medium to high importance data, and computing capacity, depending on the company's needs. Despite data centers having different sizes, it is essential one or more ventilation/cooling systems, to keep all hardware in a suitable environment for its operation and longevity.

Large companies tend to choose locations with lower temperatures to build their data centers, to minimize cooling systems energy consumption, however, these already represent more than 1% of the Global energy consumption worldwide.

“More than a third, sometimes up to one half of a data center’s electricity bill is made up of electricity for cooling”[31], [32].

In most of the world's data centers, the operating temperature does not follow any regulation, but instead, it is defined based on each manufacturer's recommendations, which itself varies from 13°C to 22°C.

“Some estimate that increasing the setpoint temperature by just one degree can reduce energy consumption by 2 to 5 percent. Microsoft reports that raising the temperature by two to four degrees in one of its Silicon Valley data centers saved $250,000 in annual energy costs. Google and Facebook have also been considering increasing the temperature in their data centers.”[33]

The challenge is to reduce the consumption of cooling systems, without sacrificing the durability of the hardware or compromising its performance.

Does increasing the working temperature of a data center, significantly influences the hardware performance?

The tech company HP presented on [34] an experiment with their new Dynamic Smart Cooling systems, where 7500 sensors were deployed in each server rack to minimize energy consumption and maximize efficiency, by redirecting cooling capacity to warmer areas inside the data center, based on real-time readings. This approach requires a substantial investment for fully deployed/working data centers, and large-scale maintenance times, to replace the outdated cooling system. It is also still one of the companies' projects in development and testing.

A WiFi solution for data center temperature monitoring was developed with ESP8266 low-power microcontrollers [35], that connect to a WiFi router to send sensor collected data over the Internet to a dashboard called Ubidots cloud. Ubidots platform supports SMS and email notifications for warning purposes; however, the proposed system was only tested slightly over a day inside a laboratory environment.

2.4. IoT communication technologies

Since the beginning of the Internet of things, possible applications have exponentially increased for all areas, from agriculture to smart homes or industry management. A recurrent problem concerning existing communication technologies, for full range applications, is either the usability cost and power consumption, or range [36].

Short-range technologies such as Bluetooth, ZigBee or WiFi can only be applied at local setups such as a small house or office since their range is limited to 10 meters, 10-100 meters, and 100 meters respectively [37].

Cellular communications are widely spread around the world, though, their usage is usually expensive and consumes a lot of energy.[38]

Low Power Wide Area Network or LPWAN technologies achieve low power consumption rates and ranges around tens of kilometers [39], by reducing the data transfer rate to minimal values, compatible with IoT applications (Figure 4 on the right).

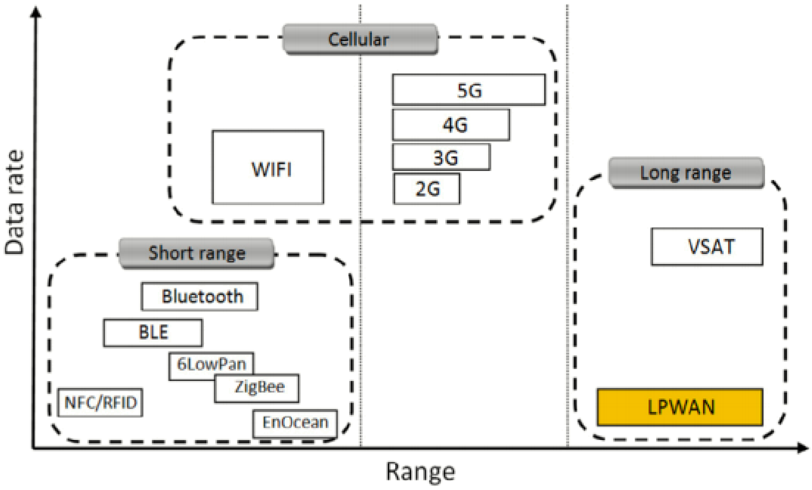


Figure 4 – Communication Technologies range according to the provided data rate. Retrieved from [36]

Three of these LPWAN technologies are Sigfox, NB-IoT, and LoRa.

Sigfox is a proprietary and patented technology that gives its users end to end communication, with a public network using an ISM unlicensed low band frequency (868 MHz in Europe, 433MHz in Asia and 915 MHz in North America) and modulated with binary phase-shift keying. This technology is limited to 100 bps which significantly reduces power consumption, however, Sigfox also established uplink and downlink daily limits and payload sizes, being 140 uplink messages with 12 bytes each, per day, and four downlink messages with 8 bytes each, per day. Sigfox network can reach a 10 km range in urban areas and a 40 km range in rural areas [36].

NB-IoT or Narrow Band IoT is a technology announced by 3GPP, LTE-based, and provided by telecommunication companies, using the same LTE licensed bands and their cellular networks, simultaneously with existing mobile technologies. NB-IoT uses quadrature phase-shift keying modulation [40], and the data rate limit is 200 kbps. This technology doesn’t have a daily message rate limit, and each message payload can have 1600 bytes. NB-IoT can reach a 1 km range in urban areas, and a 10 km range in rural areas.

LoRa or Long Range is a modulation-based technology that uses the spread-spectrum technique to adapt the data rate according to the distance from the gateway. LoRa communication uses chirp spread spectrum modulation to spread the signal over multiple channels. Similar to Sigfox, it also uses the same unlicensed operating frequencies (868 MHz in Europe, 433MHz in Asia and 915 MHz in North America), and it has a maximum data rate of 50 kbps. LoRa’s protocol, LoRaWAN, doesn’t limit the number of messages per day, and the maximum payload size is 243 bytes. LoRa can reach up to 5 km range in urban areas, and 20 km range in rural areas [36].

To summarize, Sigfox is the technology with a better range, however, the message and payload limitations are incompatible with large systems with more significant payload sizes. Sigfox is also limited to a public network service.

Despite NB-IoT having the best quality of service due to its protocol synchronicity and the most significant data rate, it is also the most expensive and energy spending technology, leading to shorter battery lives [41].

LoRa is the only of these technologies with adaptive data rates which enhances communications with devices further away from the gateway, and it also provides excellent range and a middle-term data rate, enough for our IoT applications. Energy consumption is very low since the device is always sleeping when it is not transmitting.

Chapter 3 - LoBEMS IoT System

Our proposed system LoBEMS (LoRa Building and Energy Management System), follows the principles of system integration through a common platform for multiple devices. Each device transmits data to the system using the Internet of Things (IoT) related technologies.

Taking into account the IoT system's main layers, our low-cost system development follows the next guidelines:

Device Layer - To provide easy installation, the context information is collected with low-cost, battery-powered sensor boxes, designed and programmed from scratch, with all the requirements and expansion capabilities for future upgrades. The featured sensors are temperature, humidity, light, motion, and air quality.

Communication Layer – A communication solution was programed on each sensor’s box microcontroller using LoRa technology, taking into account power consumption related to payload sizes, and the network reaches within larger buildings.

Application layer – To provide results analysis, visual interpretation and create actions for smaller application cases, we used Node-Red, an open-access software tool based on flow programming, that allowed us to develop a template-based solution, accessible both to users with technical expertise and the public in general. These templates create a descriptive analytics dashboard, with indicators and charts defined for each case scenario. Templates can present environmental analytics such as light or thermal conditions inside a building, or energy analytics, such as real-time energy readings or weekly consumption charts. From this, we developed automatic actions capable of interacting with smart lighting systems, heating/cooling systems and to create and send real-time warnings to the person in charge, using a web platform called IFTTT, or If This Than That.

For larger application cases such as ISCTE-IUL University Campus, where there isn’t a person in charge of managing the system, we developed a 3D visualization tool based on BIM models, to interact with the university community, especially students who are directly affected by each classroom environment.

3.1. Main Requirements

Following the three layers development (Figure 5), our system is structured by a physical layer with sensors and actuators, a network layer with all the IP and LoRa communications and, finally, the Application layer where all the data is fused, processed and displayed.

In Chapter 4, we present the developed work towards the implementation of energy-saving actions process in 3 application cases. First, a full system deployment at a Kindergarten, then an application case focused on human interaction towards changing behaviors at our University Campus, and finally, a test case at the University Data Center.

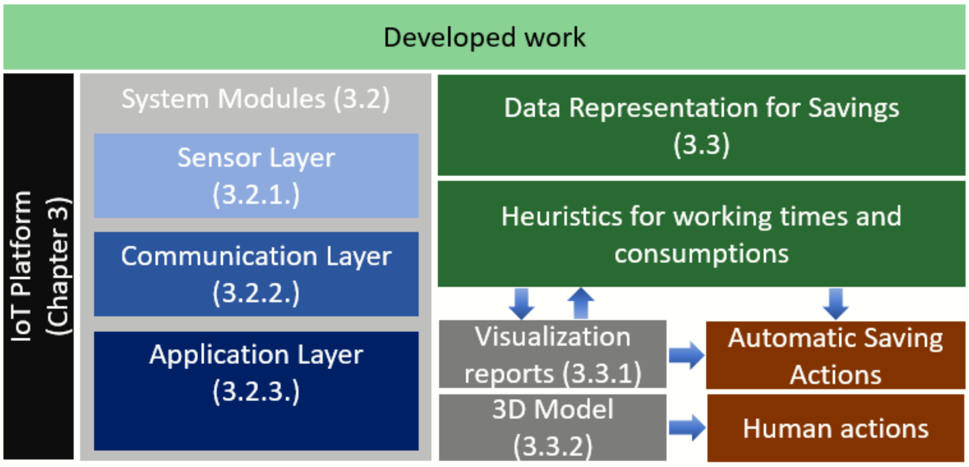


Figure 5 - IoT Platform System and related work developed for savings.

The platform can be deployed to any building, in any place. To manage, interact, and take full advantage of our system's potential, we identified as major requirements, the following:

- The need for a local person that knows the company/organization with the ability to use graphical configuration templates and from this, customize data representation and identify saving rules;
- An Energy monitor with Current transformers (CT) sensors can improve system efficiency. However, some space is required at main switchboards, otherwise, there is a need to perform installation changes;
- Sensors installation is an essential step that does not require much time or effort since our developed sensor boxes can be glued to a wall, or just left on top of an

object. They are also battery powered and can be charged with a small solar panel if required, which avoids the need to have a power outlet or use cables to power them;

- There is also the need for Lora communication; if it is not available, it is possible to buy a small gateway or assemble one with a Raspberry Pi, like in our application case, where we fully deployed the system (Kindergarten school);
- A local computer or a Raspberry Pi permanently connected to the Internet is required to deploy the Node-Red templates dashboard and a local database to store all the acquired data;
- Heating/cooling system remote interaction is mandatory; we integrated a solution with infrared commands, but others can be applied like the OpenADR (https://www.openadr.org) implementation for on/off commands, using local equipment Application Programming Interfaces (API).

3.2. System Modules

3.2.1. Hardware

The hardware equipment was chosen based on the following principles:

1. Assembly flexibility —how easy is it to assemble from of-the-self components;
2. Accuracy and Versatility—how the sensors perform;
3. Price—Low cost;
4. Modularity—Compatibility with other hardware ecosystems;
5. Power—Low/optimized consumption devices.

For assembly flexibility (1), simple and low-cost sensors were chosen, mostly used for development with Arduino and other microcontrollers, that can be easily attached to the board using jump wires, or as in our case, soldering to an empty circuit board;

To evaluate accuracy and versatility (2), we tested multiple sensors throughout the project development, and some of them had to be excluded due to unreliable outputs and low quality;

For Price - Low cost (3), the LoRa board that we used costs €13, and each sensor costs €2 on average. Comparing with commercial solutions, our developed board has a much lower cost.

One of LoRa's best features is the extremely low power consumption (5) required to transmit the data. When the board is not transmitting, it enters a sleep mode state, with an average power consumption of 3.1 mA, meaning that a 2400 mAh can power the sensor for a month, while other WiFi approaches, such as an ESP32 microcontroller, spend 230mA on average. These values were measured on the Lab, for several weeks, by storing the battery voltage on a database. The WiFi board consumption value was also measured using a similar code with the same working periods and the same sleep mode which also turns off WiFi while is not sending.

3.2.1.1. Microcontroller

To enable LoRa communication between each sensor box, it was necessary to choose a microcontroller with a LoRa radio module. There are many available options on the market, such as the ones presented in Figure 6. Because we were looking for a low-cost and low power solution, more expensive microcontrollers had to be excluded, and the chosen board was the BSFrance LoRa32u4 II.

To understand why we choose the BSFrance LoRa32u4 II, we had to evaluate which microcontroller would be the best choice for our project, and for that, we tested each of the following boards at the laboratory with basic LoRa configuration.

Seeduino LoRaWAN Heltec – WiFi LoRa (v2) BSFrance LoRa32u4 II

(a) (b) (c)

Figure 6 - Microcontroller boards with LoRa Radio module

The first LoRa microcontroller that we tested was the Seeeduino LoRaWAN in Figure 6 – (a), with a price of 44.9€ (price at the time of purchase). This LoRa board has an ATSAMD21G18 @ 48MHz microprocessor, with 3.3V logic/power, a battery management chip to regulate lithium batteries charging cycle, 20 GPIO pins (general purpose input/output pins), 18 PWM pins (pulse width modulation), and six analog inputs. The LoRa Radio module is rated as ultra-low power consumption and ultra-long-range communication since it comes with a built-in wire antenna but can also be complemented with a more powerful one [42]. This board also has four onboard Grove connectors, a connection standard that allows easy plugging of many types of sensors.

The second tested microcontroller was the Heltec WiFi LoRa (v2) in Figure 6 - (b), with a price of 21.35€ (at the time of purchase). Based on the ESP32 microprocessor (240MHz Tensilica LX6 dual-core, Wi-Fi, dual-mode Bluetooth) [43], this board comes with WiFi and LoRa radio modules, a small programmable screen, 29 GPIO pins, and a battery management chip, as the previous board.

The BSFrance LoRa32u4 II in Figure 6 – (c) had the lowest price at the time of purchase, of 13.12€. It is based on the ATmega32u4 microprocessor, 8 MHz and works at 3.3 V. It comes with 8 PWM pins, six analog inputs, and 15 GPIO pins. As the other tested boards, it also comes with a LiPo and Lion charging circuit. It doesn't have a built-in antenna, but it allows the use of an external one [44].

All LoRa microcontrollers can be easily programmed using Arduino IDE, (Integrated Development Environment), and are compatible with most of the available Arduino libraries.

After comparing each board features and testing a basic LoRa setup, we reached the following conclusions:

- During the laboratory tests, the Seeeduino LoRaWAN had a good performance, and it was easily configured using the Arduino programming sketch for the LoRa setup provided by the manufacturer.
  Despite having Grove connectors that would simplify the prototype assembly, the Seeeduino LoRaWAN was too expensive for our requirements and needs.
- The Heltec WiFi LoRa (v2), also presented good functionality and simple programming with the manufacturer provided documentation, however, we could not configure some simple Arduino libraries, perhaps due to compatibility issues, and the price was still significantly high for our low-cost solution.

- Finally, the BSFrance LoRa32u4 II was the hardest to configure due to lack of documentation, and the necessity to solder the radio module pin to the microcontroller, without any previous warning by the manufacturer.

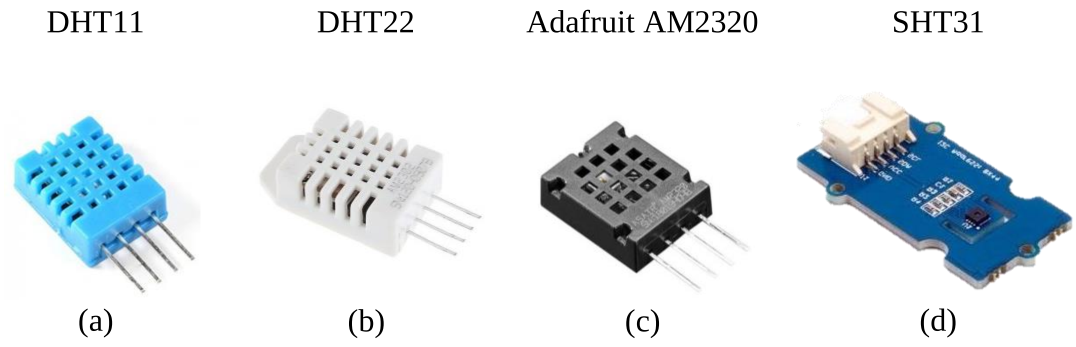
  After several tries, we managed to configure the board and use simple Arduino libraries successfully.

Despite our difficulties in programming the BSFrance LoRa32u4 II board, we chose to use it for our project since it had all the required pins and more for future upgrades, battery management, good performance, and extremely low price.

3.2.1.2. Sensors

There are many different sensors for each type of measurement on the market, each one with its own characteristics, range, precision, and accuracy. Because our system requirements are also related to the application cases, we had to understand which sensors were better for each application and which sensors had to be left out.

The main environment variable that our system is based on is temperature and humidity. Considering the available material, we tested four different temperature and humidity sensors, listed in Figure 6 below.



DHT11 DHT22 Adafruit AM2320 SHT31

(a) (b) (c) (d)

Figure 7 - Tested Temperature and humidity sensors

To compare the sensor reading with the real temperature, we recorded a reading every 15 minutes for 24 hours and compared them with manual readings taken by a high precision infrared thermometer and a weather station placed at the laboratory.

We started by testing the DHT11 in Figure 7 – (a), the cheapest sensor, costing around 4€. With a temperature precision of ± 2°C, the results were expected, and none of the readings had an error lower than 1°C from the real measurement.

With the DHT22 in Figure 7 – (b) costing 9€, results were more precise, presenting only accuracy errors of less than 0.5°C, probably because the sensor accuracy itself is 0.5°C. For our sensor testing application case at the Data Center, it wasn't enough due to the room's nature and the hardware sensitivity requirements.

The Adafruit AM2320 in Figure 7 – (c), with a cost of 6€, was tested as a cheaper alternative to the DHT22 but is precision was very similar to the DHT11, of ± 2°C. The only advantage of this sensor would be the I2C communication protocol (Inter-Integrated Circuit) implemented on the sensor.

The most expensive sensor is SHT31 in Figure 7 – (d), with an average cost of 12.6€ it presented the best accuracy and precision results. With a precision of ± 0.3°C and I2C communication protocol, errors were minimal, and we considered this as the best option for our Data Center application case.

As for the Kindergarten and the BIM model application case, we considered the DHT22 as the best option considering that is error rate justifies the slightly increased price over the other low-cost options.

For the other application cases, more sensor types were required, and because of that, we tested a few options for light sensors, motion sensors, and an air quality sensor.

The light sensors in Figure 8 were tested under different light conditions such as natural light only, artificial light only, and both.

Grove – Light Sensor v1.2 based on GL5528

Light sensor module based on GL5528 photoresistor

(a)

(b)

Figure 8 - Tested Light sensors

The first light sensor that we tested was the Grove – Light Sensor v1.2 in Figure 8 – (a), equipped with a Grove connector and an LM358 chip that converts light intensity into a voltage and outputs the analog signal.

The Light sensor module based on GL5528 photoresistor presented in Figure 8 – (b), is very similar to the previous sensor, also including an LM358 chip.

Despite the similarity, after testing, we concluded that the Light sensor module (Figure 7 – (b)) was a better option since it achieved much better results than the other sensor when tested with brighter light sources.

Motion sensors in Figure 9 were tested for false positives (when the output is one but should be zero).

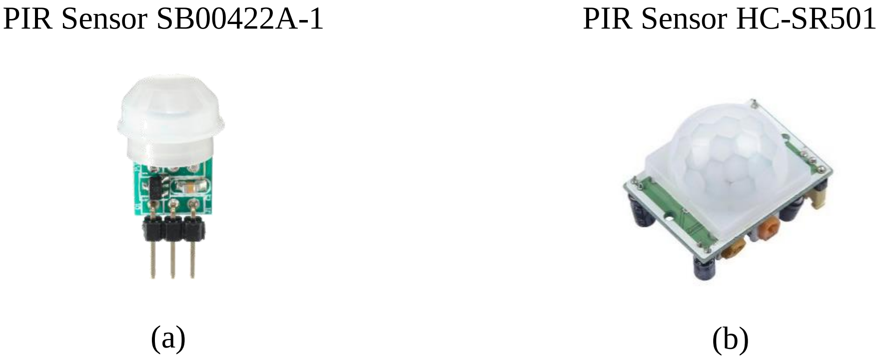


Figure 9 - Tested Passive infra-red motion sensors

To test both Passive infra-red motion sensors, we placed them near the laboratory door where people pass frequently, and we compared the false negatives. After analyzing the results, the PIR sensor in Figure 9 – (a), had much more false negatives than the PIR sensor in Figure 9 – (b). This can be explained by the adjustable screws of the PIR Sensor HC-SR501 that allow increasing or decreasing the sensor range, and also the time the sensor stays on after a detection. The second adjustable screw is very important because the LoRa board only reads the sensors from time to time, and that means if the PIR Sensor SB00422A-1 detects motion during sleep time, it won't count.

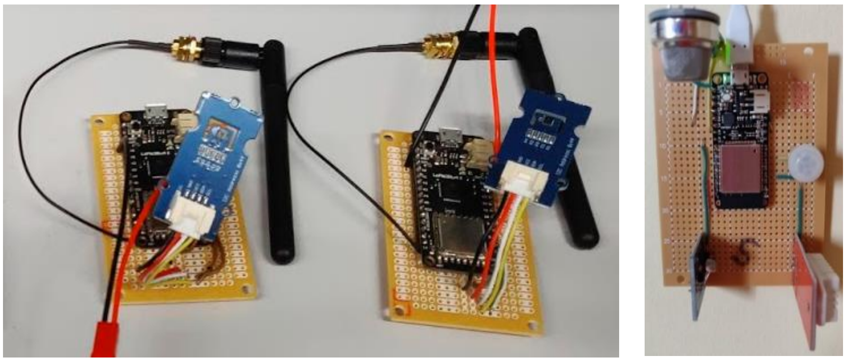
The air quality sensor MQ-135 sensor presented in Figure 10 is suitable for detecting Ammonia (NH_3), nitrogen oxide (NO_x), alcohol, Benzene, smoke, and Carbon

Dioxide (CO_2). The sensor was calibrated by the manufacturer, but it was also tested with a few substances such as alcohol.

Figure 10 - MQ-135 Air Quality sensor

3.2.1.3. Developed prototype

Each microcontroller board and the required sensors were soldered to perforated circuit boards, accordingly to their purpose. Figure 11 - (a) sensor board prototype was developed for the Data Center with a single, high precision temperature and humidity sensor, and it was also used for the 3D BIM model application case. Figure 11 – (b) was developed accordingly to the kindergarten owner's requirements.



(a) (b)

Figure 11 – (a) presents the developed sensor board prototype for the Data Center application case, and (b) presents the developed sensor board prototype for the Kindergarten Application case

To store the hardware was necessary to design portable, lightweight, and functional boxes that could fit between the server shelves at the Data Center, and that would be large enough to store the sensor battery.

A 3D box was designed with AutoCAD (Figure 12), a design software mostly used to create 2D and 3D models. The box was then 3D printed at ISCTE's Fabrication

Laboratory, or FABLab, with a biodegradable material called Polylactic acid, obtained from renewable resources such as sugarcane [45].

Figure 13 presents the final sensor boxes prototypes for our application cases.

Figure 12 – AutoCAD designed box, before printing

To provide enough battery for the normal sensor operation, we used Lithium Polymer rechargeable batteries with a capacity of 2400 mAh each, and a small solar panel to restore its power over time since the sensors are configured to send data every 5 min.

The BSFrance LoRa32u4 II microcontroller allows deep sleep function, which turns off all the main components for a defined period of time and maximizes the battery life duration.

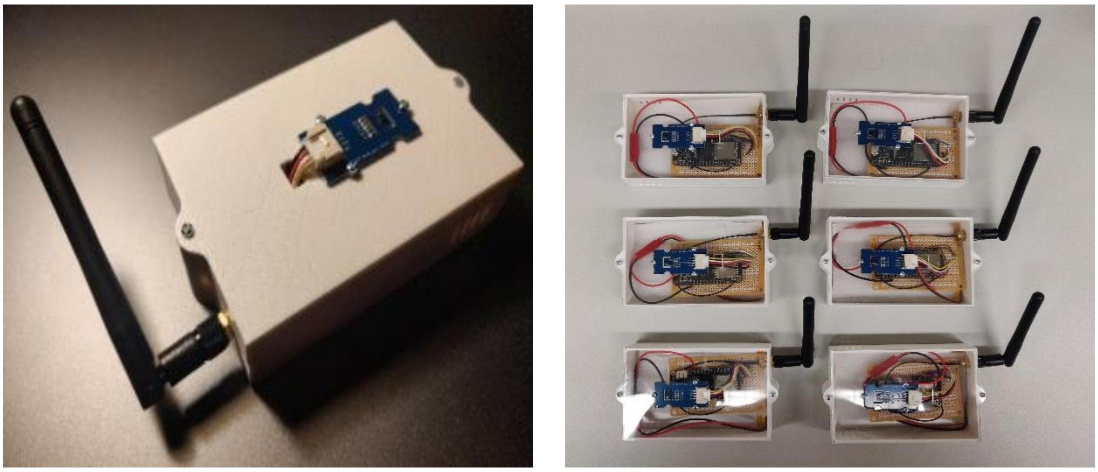


Figure 13 – Final sensor prototypes

A detailed power consumption evaluation of the LoRa board was performed at the lab by comparing the battery duration with the amount of data sent by the sensors and the periodicity. The results concluded that increasing periodicity to 10 min (the double), also doubles the battery duration as expected, because during sleep mode the board spends only 0.005 mA which means that only 0.16% of the energy is spent on sleep mode, while 99.84% of the energy is spent when it sends data to the gateway.

To test the effects of reducing the size of the messages sent by the board, the sensor's values were encoded using simple arithmetic operations, for instance, the humidity reading was divided by four in order to reduce the size of the number and therefore optimize the payload sent over LoRa.

We managed to cut the message size by half, and the results prove that battery duration was extended more than two and a half times. This can be explained because the board sending time is reduced and since the message is smaller than before, the microcontroller processes it faster and therefore spends less energy, 2.3 mA on average.

We can assume, based on our experiments, that payload size optimizations have slightly more impact than changing the sending periodicity, however, if combined together, this approach can extend the battery duration much more than previously expected.

3.2.1.4. Other hardware

All the computing power to manage the LoRa network, process and store the received data, and present it to the users, is provided by a Raspberry Pi Figure 14 – (a), running Raspbian operating system and all the software required for the system to run properly.

To provide more interoperability with IoT related devices and improve our system effectiveness, we also used an energy monitoring system, WiFi light switches, WiFi plugs, and a WiFi – infrared bridge device to control the air conditioning systems with programmed infrared signals.

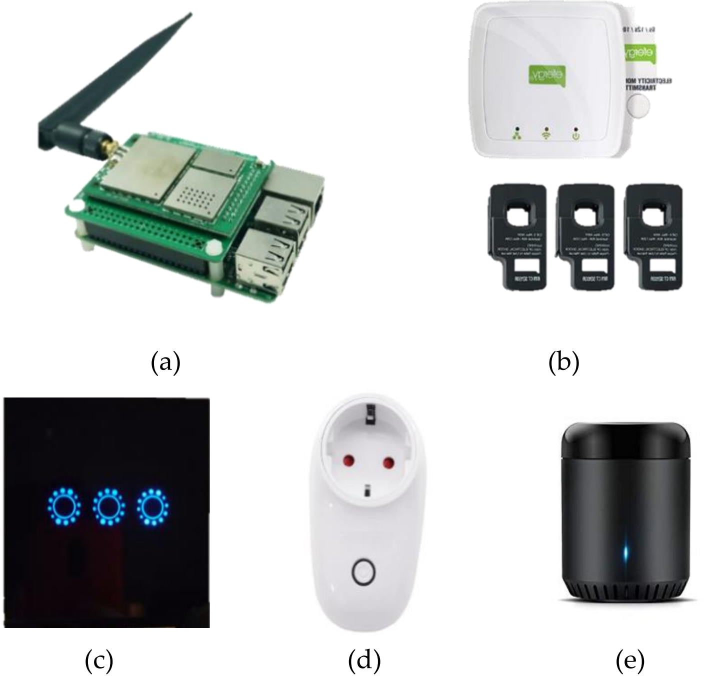


Figure 14 - Measurement and control hardware. (a) Raspberry Pi with LoRa Hat; (b) Energy monitoring system and amperometric clamps; (c) Smart wall switch; (d) Smart power socket; (e) WIFI/Infra-Red Emitter

The Raspberry Pi, Figure 14 – (a) is the core of the system, functioning as a LoRaWAN gateway, with an iC880A LoRa 868MHz concentrator module, and as an application server LoRaWAN connection with The Things Network (TTN) when LoRa network isn’t available, data processing and storage functions.

The energy system Figure 14 – (b) is an ongoing solution that uses three amperometric clamps attached to the main power cables, to detect the current that is passing throw them, and sends the data over the Internet to a dedicated web platform. This solution was integrated into our system.

Smart wall switches, Figure 14 – (c) were placed to work as an interface between the ceiling lights and WiFi, and the same with smart sockets, Figure 14 – (d) and appliances, allowing their control over the Internet and therefore the automation system.

A WiFi controlled device that emits infra-red signals, Figure 14 – (e) was used to send commands to air conditioning units, mimicking their remote control. This device captures Infrared signals and stores them as commands. Each command works as the A/C remote buttons, allowing the system to change each parameter independently such as fan speed, temperature, or working mode (winter/summer/dehumidifier).

We also used a commercial solution provided by Lansitec, for LoRa Outdoor temperature, and humidity sensors, to monitor the environmental conditions around our study cases. These sensors have an International Protection classification of 65, which identifies devices that are water-resistant (Figure 15).

Figure 15 – Lansitec LoRa Outdoor temperature and humidity sensor

3.2.2. Communications

To connect all sensors, actuators, and existing systems, our system uses IP communication by WiFi and ethernet, LoRa, and Infrared.

TCP/IP over WiFi connects all devices, actuators, and auxiliary systems to the Raspberry Pi, where HTTP requests are originated to change devices states.

Infrared is used to interact with devices, controlled by Infrared commands such as Air conditioning units.

LoRa communication connects our developed sensors to the LoRa network and the Internet.

There are two ways our developed sensors could connect to the LoRa network:

- ABP - Activation By Personalization, which assumes that the device already has the session keys.
- OTAA - Over The Air Activation, more commonly used, establishes a connection using a handshake process with the network server.

Since ABP wasn't implemented at ISCTE University Network, our system only uses OTAA.

Each device comes with a set of 3 hexadecimal identifiers, written outside the sensor or programmed into the board's code such as our development boards.

The DEVEUI identifier uniquely identifies the device. The APPEUI, or, JoinEUI (since version 1.1 of the LoRaWAN Protocol) uniquely identifies the server that processes the "join" request on the network, and the APPKEY corresponds to an AES-128 encryption key, used to generate other session keys, encrypted communication, and exchange data with the network server [46].

Once the device is added, it is necessary to associate an application, which in this case, is a developed server, running on the Raspberry Pi, connected to the same network.

The handshake process is described in Figure 16 [47], [48]. The device starts by requesting the network server, the public key (Figure 16 -1), and after receiving the answer (Figure 16 – 2), it encrypts a join request message with its security keys and the received one (Figure 16 – 3), before sending it to the network server. At the same time, the device sends the encrypted AppKey in parallel with the request (Figure 16 – 4). With the encrypted AppKey, the network server is able to decode it with its own private key and then decode the join request with the previously decoded message (Figure 16 -5). Finally, the received join request is validated, and a join accept message is generated and sent back to the device (Figure 16 – 6).

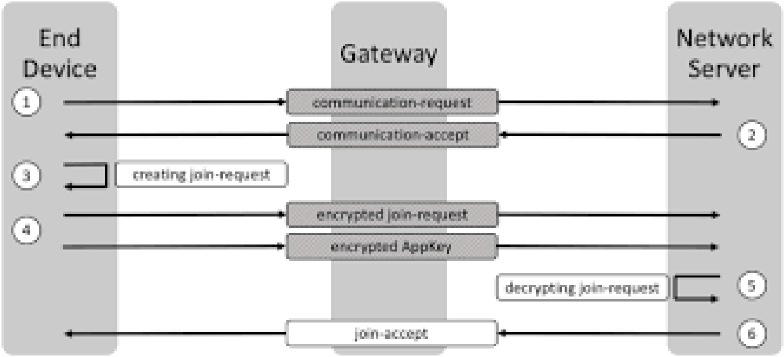


Figure 16 – LoRa Over The Air Activation, handshake process. Retrieved from [47]

LoRa is a growing Internet of Things technology, and because of that, international telecommunications companies like CISCO have already developed their own LoRa solutions. ISCTE University was one of the first places where CISCO tested its solution by placing 2 LoRa Gateways, with High-performance Antennas, on the highest building rooftop, and inside the building itself to provide better indoor coverage.

Scenario 1

In this project, the test application case at the University Data Center uses CISCO's solution. A schematic of the system using this network scenario is presented in the next Figure 17.

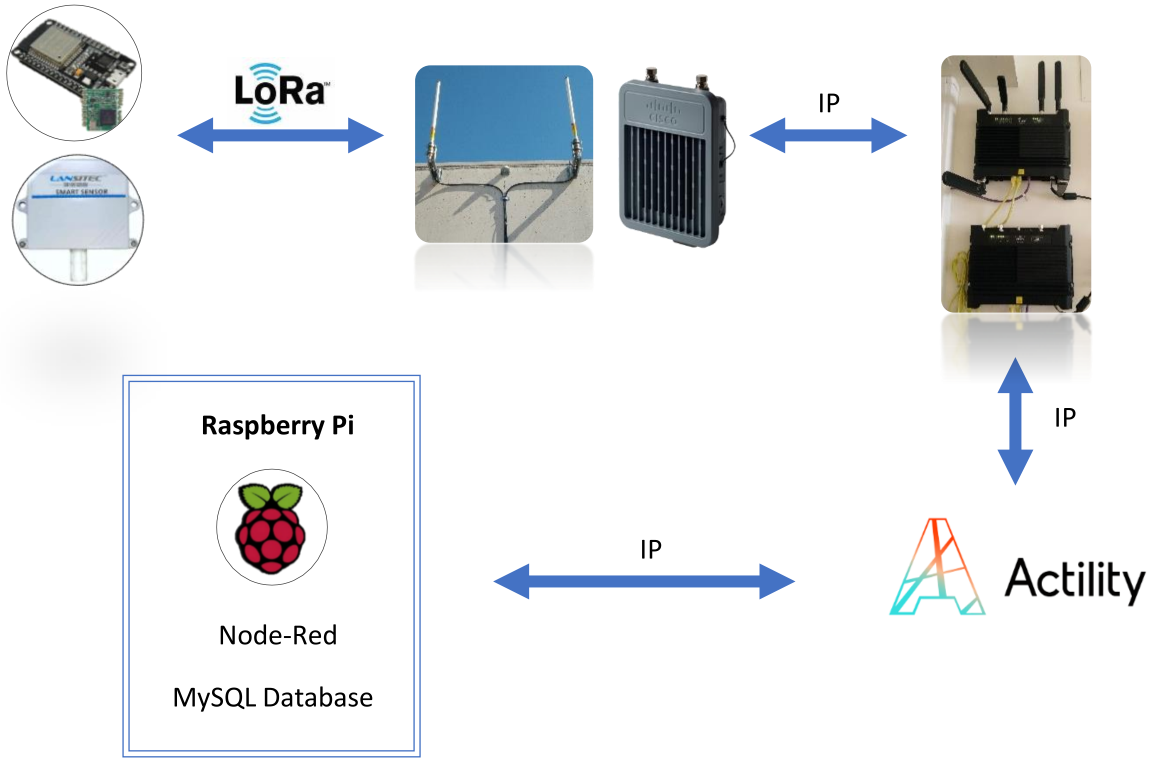


Figure 17 – System communication network scenario with CISCO's LoRa solution

In this scenario, each sensor connects to the LoRa gateway (indoor or outdoor), which is responsible for forwarding all messages to the Actility network server, through IP connectivity, provided by 2 CISCO routers. The Actility server is where users determine the end applications for each device, in our case an HTTP server running at the Raspberry Pi. The Raspberry Pi is where the database and our chosen visualization tool, Node-red, is deployed and ready to be accessed from any device.

Scenario 2

In a second scenario, the absence of LoRa network connectivity can be resolved by using a TTN Gateway.

As a member of the LoRa Alliance, The Things Network, or TTN, is a worldwide project focused on developing open access and secure IoT network based on LoRa technology and LoRaWAN protocol [49]. One of TTN's best features is the possibility to create a Gateway with relatively cheap and available hardware. The software setup is fully documented and, in a few hours, the Gateway is ready to receive and send/receive messages to/from sensors.

Since at the Kindergarten application case, there wasn't a nearby LoRa gateway, this was the chosen approach for the full system deployment.

The system network schematic with a TTN Gateway scenario is presented in the next Figure 18.

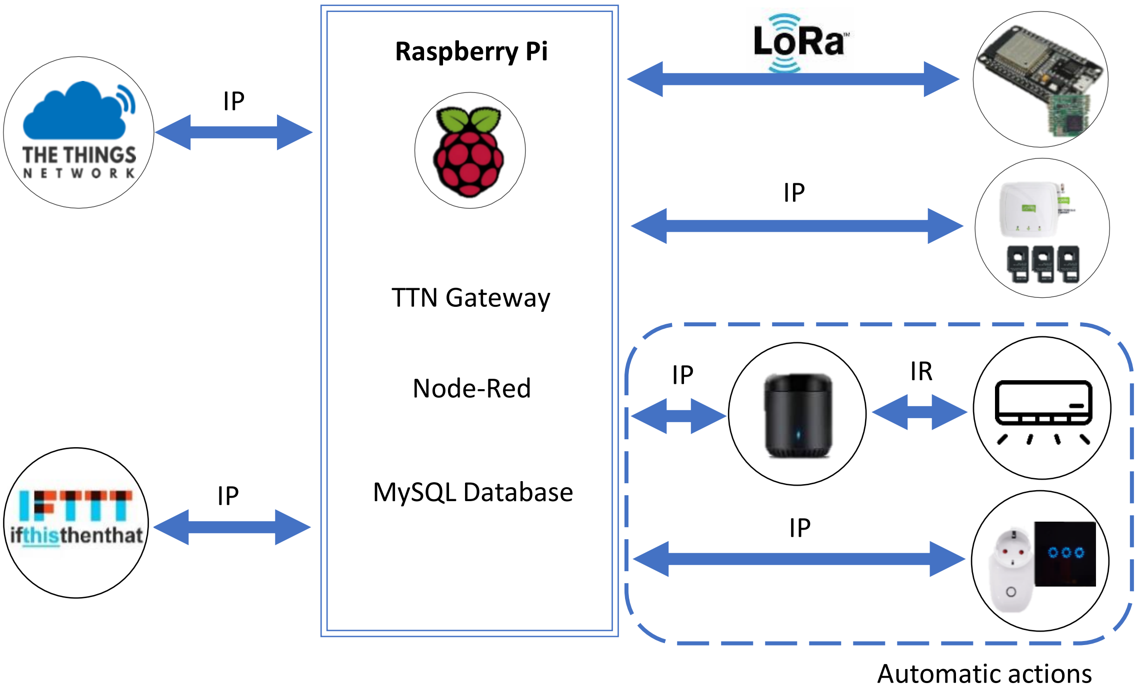


Figure 18 - System communication network scenario with TTN gateway solution

In this scenario, the network is managed from The Things Network website, after the Gateway has been properly configured on the Raspberry Pi. TTN's Web console provides a user-friendly interface to make device management as easy as possible. Besides adding new LoRa devices, it allows the integration of a variety of services such as HTTP, however, the Application server that we used, connects directly to TTN.

If This Then That, or IFTTT, is a free Web platform that allows the interaction between services and dozens of different Application programming interfaces (APIs), provided by many manufacturers, like weather service, time service, HTTP service, voice assistant APIs or smart devices APIs.

As IR emitters, WiFi switches, and power sockets require interaction with their API to be remotely controlled. This is done using IFTTT HTTP service, and all notifications are also sent using IFTTT email services.

3.2.3. Application

The application layer is composed by services and applications running on the Raspberry Pi (aside gateway functions), such as Node-Red, Maria-DB, and the tools developed to represent and extract information, namely the Template-based dashboard and the 3D BIM visualization tool.

Node-RED is open-source software available for many platforms including the Raspberry Pi. It is a flow-based programming software (example of Node-red backend in Figure 19), created specifically for IoT applications where it is possible to connect APIs, physical devices, other network interfaces, and web services. It also allows the programming of rules in JavaScript to run or keep from running specific flows. Node-Red also allows the installation of extra features such as a TTN node, that provides connectivity to TTN or a connection to a local MySQL database.

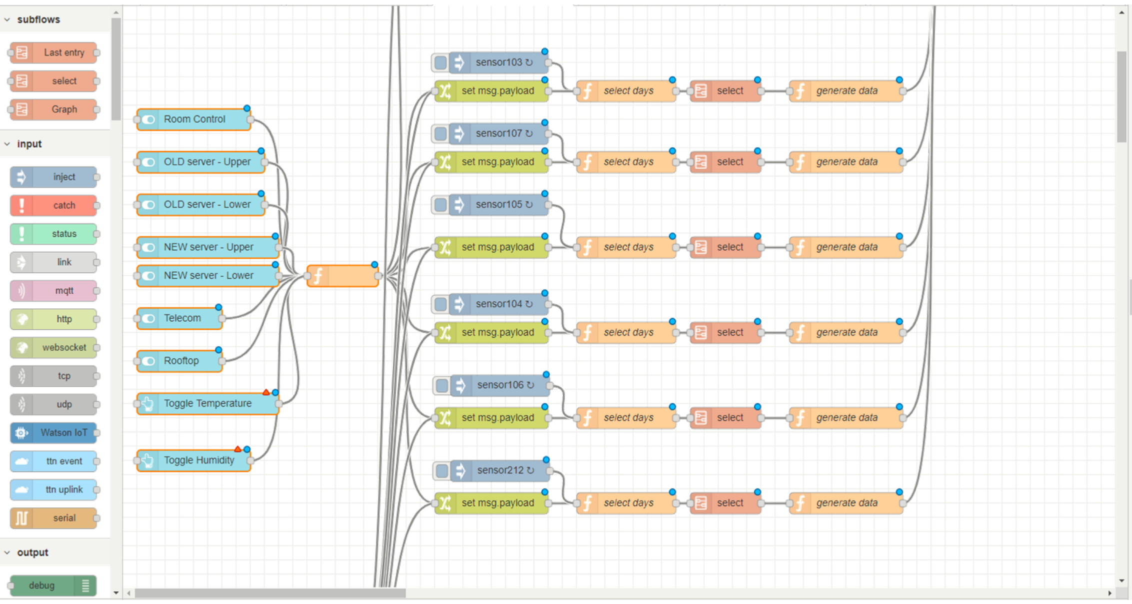
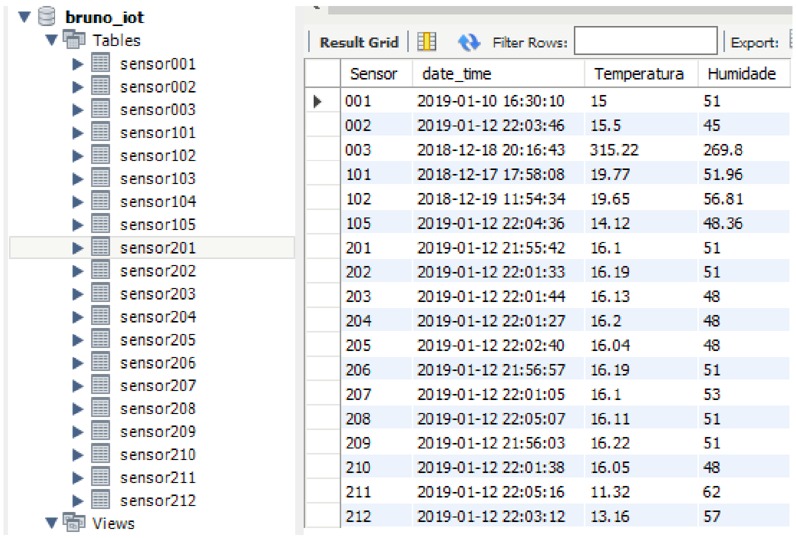


Figure 19 – Node-Red backend example for one of the application cases

Our template approach, as previously mentioned, uses Node-Red functionalities to display custom indicators and charts related to the user needs. This approach is further discussed in Chapter 3.3 – Data Representation for savings.

All the collected data is stored inside the MySQL database, structured into individual tables, one for each sensor (Figure 20). The stored variables correspond to the date and time each message was received, the temperature value in degrees Celsius, the relative humidity value, a light value in percentage, motion value as 0 or 1 according to the case, air quality value in percentage, and the battery value in volts. Some network-related variables are also stored, such as frame counters, Received Signal Strength Indicator or RSSI, Signal-to-noise ratio or SNR and the Spreading Factor value.

For the outdoor Lansitec sensors, only time and date, temperature and humidity were stored.



Sensor	date_time	Temperatura	Humidade
001	2019-01-10 16:30:10	15	51
002	2019-01-12 22:03:46	15.5	45
003	2018-12-18 20:16:43	315.22	269.8
101	2018-12-17 17:58:08	19.77	51.96
102	2018-12-19 11:54:34	19.65	56.81
105	2019-01-12 22:04:36	14.12	48.36
201	2019-01-12 21:55:42	16.1	51
202	2019-01-12 22:01:33	16.19	51
203	2019-01-12 22:01:44	16.13	48
204	2019-01-12 22:01:27	16.2	48
205	2019-01-12 22:02:40	16.04	48
206	2019-01-12 21:56:57	16.19	51
207	2019-01-12 22:01:05	16.1	53
208	2019-01-12 22:05:07	16.11	51
209	2019-01-12 21:56:03	16.22	51
210	2019-01-12 22:01:38	16.05	48
211	2019-01-12 22:05:16	11.32	62
212	2019-01-12 22:03:12	13.16	57

Figure 20 – Database query showing each sensor table and the last reading of each sensor in that moment

Unity is a 2D and 3D development software that allows us to integrate a converted BIM model of a building, with our system variables, by introducing C# scripts into each room's volume, and change its color according to the variable being analyzed. A more detailed description is provided in Chapter 4.2, Application case at ISCTE Campus.

3.3. Data Representation for savings

Our developed system was divided into two visualization methods, one for small/medium size buildings, where it is possible to centrally manage the system, and another tool for large buildings, where centralized management is not possible. The next table 2 presents the two developed visualization methods.

Table 2 – Developed approaches to represent data and create savings

Approach	Application	Interaction method	Savings
Node-Red Template-based dashboard	• Dashboard based on pre-existing templates; • Sensors indicators and charts; • Real-time data and statistics;	• Centralized system management; • Requires initial programming and the manager supervision to adapt the system to his needs;	• Automatic control over specific systems such as ACs, lights and smart plugs; • Daily schedules and saving rules defined by the person in charge, based on collected heuristics;
BIM 3D building model	• Multiplatform application for 3D viewing; • Real-time color indicators for each sensor's location and variable	• People direct intervention; • Available for mobile devices; • Real-time warning detection and visualization;	• Real-time alerts allow faster interventions; • Human actions; • System spreading among the community; • Possibility to use gamification techniques to influence behaviors

Our first solution is based on pre-defined templates (described in the next section 3.3.1), that can be customized by the person in charge, to adjust to each building's requirements. The dashboard presents collected data and statistics, to allow the extraction of heuristics, in which daily schedules are based.

The second solution (described in the next section 3.3.2), is based on a 3D building model with real-time data being displayed at strategic places around the selected building.

3.3.1. Pre-defined Templates

The pre-defined templates illustrated in Figure 21, were based on previously identified heuristics, that allow users without programming skills to retrieve important information about their company environment and power usage, from automatically generated charts and indicators. With this information, the user can activate automatic rules, such as temperature control inside the building, or manually control devices, accordingly to their needs. These templates were programmed in Node-Red, oriented to three re-defined goals based on MDA (Model-Driven Approach) [50], in software code development:

- Environment perception (according to the application case) with the data representation of temperature in °C, humidity in relative % luminosity in % (considering the max and min detected), air quality in % (considering the max and min detected), and presence. The user can change each classroom temperature interval;
- Global Energy Consumption with Real-Time, hourly, and daily power consumption in watts and kilowatts. These templates are useful to identify working anomalies in A/C or other systems;
- Individual Energy Consumption with A/C's working time in minutes or hours per day, and a graphical interface to turn on or off individual devices, such as lights or plugs. These templates are used to defined working time periods of individual equipment.

Our platform until the moment has the following developed templates that can be re-used and applied to different cases:

Template 1—Dashboard visualization of environment variables. The goal of this template is to gather real-time readings from each sensor and present them in gauges and similar indicators;

Template 2—Time window graphic of the environment variable. This template allows users to choose the day and window time (start hour and finish hour) and variable to represent. This template’s goal is to present a time window overview of the environment variables. An example of this output is a chart, where the graphics allow seeing a time overview of this environment collected data;

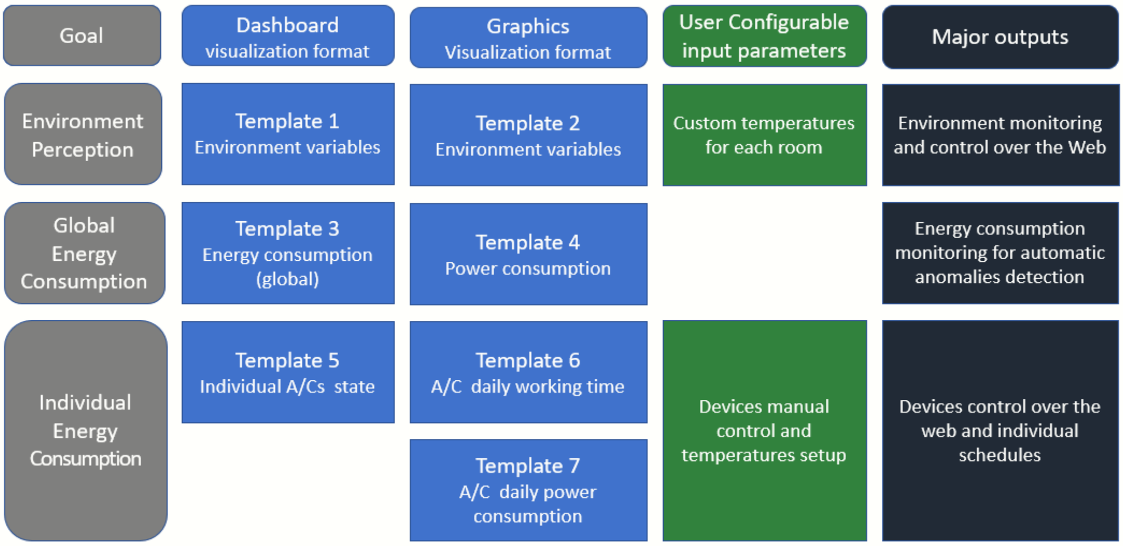
Template 3—Energy indicators. This template uses the current date to show, besides real-time consumption, the last hour and last 24 hours statistics with minimum and maximum values divided by color groups;

Template 4—Energy consumption charts. This template concatenates all power consumption records of each day and presents them in a linear chart and an accumulated chart;

Template 5—User controllable devices and variables. A/Cs current state indicators, with user inputs for variables setup, such as each room temperature, and manual device's controls. This template allows the user to choose equipment (this case A/C);

Template 6—Detailed usage of each device. This template's goal is to show the user, on a bar chart, how much time in minutes, each A/C (the biggest energy consumer device) worked in each room, per day. Each room is presented in a different color;

Template 7—Global comparison chart. This template joins multiple variables with interest for the user to relate. In this case, the chart where this template was applied, joins the sum of all A/Cs working time, in hours (green bars), the daily energy consumed in kilowatts (white bars), the maximum district temperature in °C (red bars), with the minimum district temperature (blue bars). This allows the user to relate all these variables with each other and detect patterns such as higher A/C working time when the district minimum temperatures are lower.



Goal	Dashboard visualization format	Graphics Visualization format	User Configurable input parameters	Major outputs
Environment Perception	Template 1 Environment variables	Template 2 Environment variables	Custom temperatures for each room	Environment monitoring and control over the Web
Global Energy Consumption	Template 3 Energy consumption (global)	Template 4 Power consumption		Energy consumption monitoring for automatic anomalies detection
Individual Energy Consumption	Template 5 Individual A/Cs state	Template 6 A/C daily working time Template 7 A/C daily power consumption	Devices manual control and temperatures setup	Devices control over the web and individual schedules

Figure 21 - Templates Overview

Together with other systems integration and system management, savings can be easily obtained. This approach was implemented in our first application case, the Kindergarten school.

3.3.2. 3D BIM visualization tool

A series of colorimetric scales, allows users to identify concerning areas and real-time warnings, to take actions.

By creating a 3D BIM-base visualization tool and allowing people to observe and interact with the 3D model of the building, on tablets placed at strategic places like corridors, user response increases, and real-time warnings provide the community an overview of the current building state. This approach also decreases the time required for an alert to be dealt with and creates awareness in the university community. The possibility to introduce gamification techniques into this approach can substantially increase its effectiveness.

A pre-existing 3D BIM model of one of the University buildings (previously presented in Figure 3), was used and integrated with our system to evaluate this approach, with application case at ISCTE-IUL University Campus.

The next Figure 22 presents the user interface, for the ISCTE-IUL University academic services, where we tested the visualization tool.

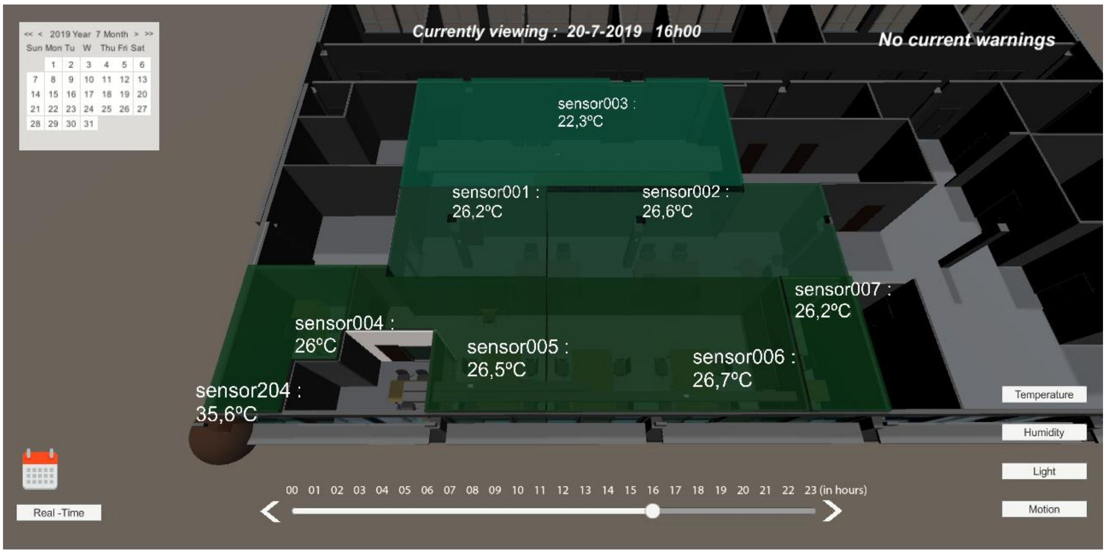


Figure 22 - User interface with temperature mode selected for 20-07-2019 at 16:00h

A more detailed description and evaluation of this approach are presented in chapter 4.2., "Application Case at ISCTE-IUL Campus".

Chapter 4 - Application Cases

Our system was implemented in 3 different application cases:

- A private Kindergarten with full system deployment of sensors, network, Node-Red template-based visualization tool for management, integration with the building light system, air conditioning system, and automatic savings, based on predefined automation and user-made rules.
- A University campus room cluster with sensors deployment, together with a Building Information Model, or BIM, integrated with the system using Unity. This Model allows a more direct user approach with 3D visualization, aiming to influence user behavior towards savings since, in a public space, people can interact with light and heating/cooling systems.
- A Data Center, for testing and measurement of environment variables, as a request from the University.

4.1. Application Case at Kindergarten

As technology progresses and people become aware of all the new possibilities for well-being improvement, energy savings, and resource management, local companies try to invest and obtain visible results.

In reference [51], the authors studied what encourages people to increase their home's efficiency and how they attempt to do it. Most popular approaches are focused on home renovations to decrease energy costs, however, people don't know how much energy it is possible to save by reducing the defined A/C temperature difference, compared to the outdoor temperature, or the potential a building and energy management system has to increase savings and automate some actions.

In our case study, the owners were already taking measures to increase the school's efficiency and reduce energy costs, however, they were also aware of technology's potential to increase both savings and comfort, and that awareness led them to accept the project immediately.

"Pequenos Sorrisos, Lda.", a private kindergarten (Figure 23) with 50 students and 12 rooms of 16 to 40 m2 located at Amadora, Lisbon, Portugal, (latitude 38.7664 and longitude −9.2388) has been working on a sustainability project since 2016, which includes a real-time energy monitoring platform available on the market, total information digitalization and total lighting systems upgrade to LEDs. The building was constructed in 2007, and it has natural light from all sides, despite being currently surrounded by vegetation, as shown in Figure 23. The kindergarten also has electric blinds that are open during working hours.

This case study was chosen because the building category is related to our work environment, and it presents appropriate dimensions for our project deployment. The owners gave us the opportunity to design and implement the system following their guidelines, and conduct our project, potentially increasing the quality of education in our city in the process.

Figure 23 - Kindergarten, the case study building

Some detected issues were related to standby consumptions, however, the main part of the energy bill was due to kitchen appliances and the air conditioning system.

In reference [52] the authors present an "overheating risk and thermal comfort assessment of a prototype building to understand what causes a major impact on the building environment and how it affects the occupant's comfort and health". The authors concluded that besides the number of people using each room, the building construction materials could have different capacities to absorb heat and therefore increase or reduce the time it takes for the building to heat up or cool down. Also, the building orientation has a major impact on the environment inside because facades more heavily exposed to direct sunlight can heat up much faster than others. It was also concluded that human interaction could reduce the impact of these factors, for instance, opening the windows when the outdoor temperature is more comfortable, and the airflow can regulate indoor temperature.

Since our case study building has windows from all sides, solar exposure could be a problem, however, the vegetation around the North, East and West facades, keeps most direct solar radiation from reaching the windows. Each classroom at the kindergarten has a different capacity, so it is expected that it affects each room's temperature and humidity. As the authors in reference [52] also concluded, on our case study, employees did not know when to use natural ventilation, and sometimes, they would open the windows with much less comfortable temperatures outside, or even with the A/C turned on.

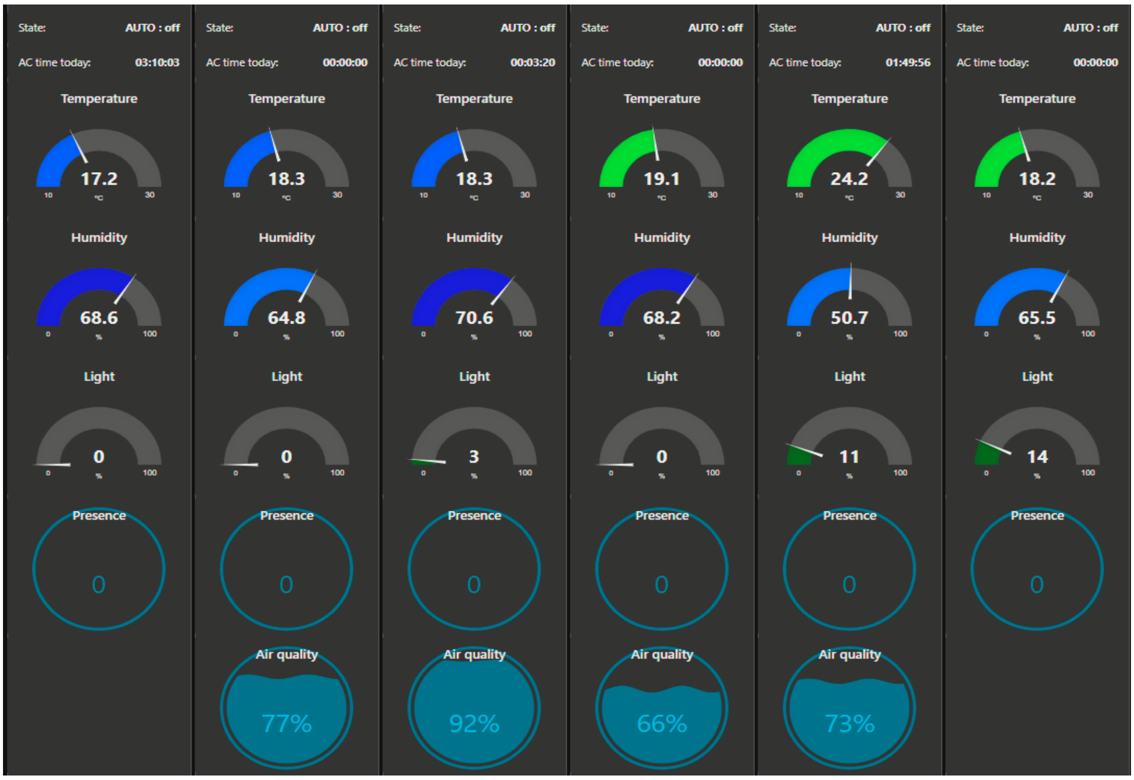
As dealing with standby energy consumption was unavoidable, replacing kitchen appliances would introduce higher costs and because managing the air conditioning system is very time consuming and reliant on staff behavior, the owners agreed to integrate a LoRa intelligent automation system to monitor each room's conditions and interact with the air conditioning system, the lighting (which was often unintentionally left on), and smart WiFi sockets, based on the collected and processed information.

For this application case, we can summarize the proposed goals:

- Web platform permanently accessible from any device, at any time;
- Individual monitoring of 6 classrooms with temperature, humidity, light, motion, and air quality variables;
- Integration with an energy management system, in real-time, with statistics;
- Ceiling lights integration with the possibility to set timers and rules;
- Smart plugs integration for stand by consumption reduction;
- Automatic Smart Air conditioning control with timers and rules, based on each room variables;
- Manual control of all systems through the web.

4.1.1. Data Visualization Reports

Developed templates allow users to create easily personalized reports based on these pre-defined templates where users can choose visualization parameters. This approach allows users with low knowledge to develop or create personalized reports as a big picture, and from this, the creation of local and personalized saving rules for automatic actions can occur. Most indicators provide the user with a quick and easy way to see the current state of a classroom, for example, if the light is on and the room is empty, or if the room is too cold and the air conditioning is off. Each column on the dashboard (Figure 24), represents a single room with all the sensor's values and other values such as current air conditioning state, daily air conditioning working time and current light state. These types of figures allow the visualization and the users' perceptions about environment parameters to be developed based on data available from local implemented sensors.



State: AUTO : off	State: AUTO : off	State: AUTO : off	State: AUTO : off	State: AUTO : off	State: AUTO : off
AC time today: 03:10:03	AC time today: 00:00:00	AC time today: 00:03:20	AC time today: 00:00:00	AC time today: 01:49:56	AC time today: 00:00:00
Temperature 17.2	Temperature 18.3	Temperature 18.3	Temperature 19.1	Temperature 24.2	Temperature 18.2
Humidity 68.6	Humidity 64.8	Humidity 70.6	Humidity 68.2	Humidity 50.7	Humidity 65.5
Light 0	Light 0	Light 3	Light 0	Light 11	Light 14
Presence 0	Presence 0	Presence 0	Presence 0	Presence 0	Presence 0
	Air quality 77%	Air quality 92%	Air quality 66%	Air quality 73%	

Figure 24 - Node-RED Dashboard, indicators and real-time consumption view

These values, mainly around room temperature, can be used together with energy consumption to create trigger temperature rules to turn on/off A/C or increase/decrease the power.

At a secondary window (Figure 25) on the dashboard, all variables are displayed inline charts with a 12-hour time period. Air quality percentage is calculated by comparing the sensor reading with the maximum and minimum readings ever detected, since the used sensor does not allow a direct conversion of the output signal into a specific unit.

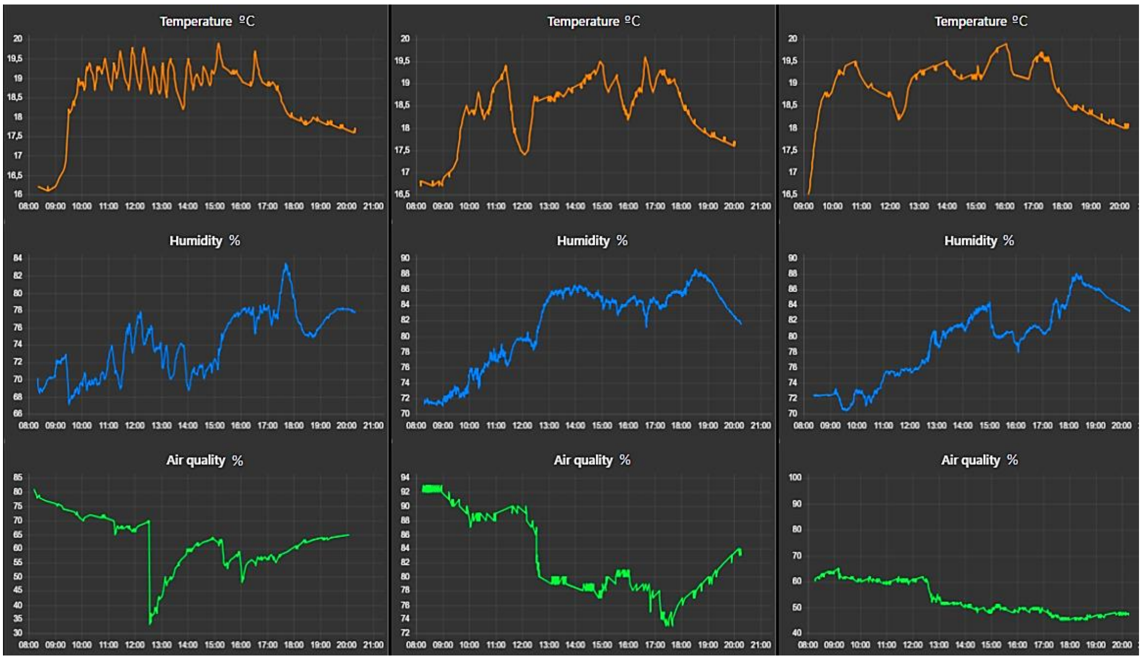


Figure 25 - Node-RED Dashboard, Temperature charts in Degrees Celsius, Relative Humidity Charts, and Air Quality charts in percentage values.

As part of the existing energy management system integration, the available API was used to retrieve real-time data presented on the energy management tab (Figure 26) was more accurate than the solution provided with the system because the original website is limited to a minimum real-time consumption of 100 watts, which reduces this tool’s capabilities.

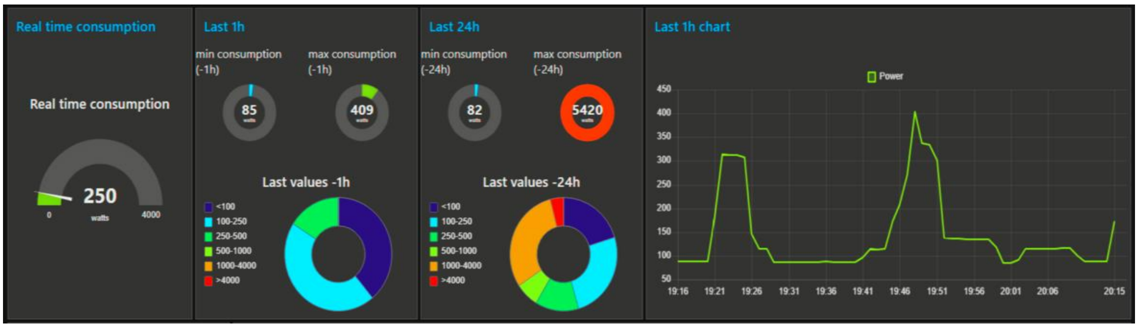


Figure 26 - Node-RED Dashboard, Real-time, last 1h, and last 24h consumption indicators.

This tab also presents indicators of the real-time consumption (measured every 15 seconds) and the minimum and maximum recorded consumption values within the last hour and the last 24 hours.

These values are divided into categories with different colors, with cold colors equivalent to lower consumption values, and warm colors equivalent to higher consumption values.

This feature was requested by the school owners as a preventative measure for unwanted energy waste, especially on weekends.

A notification email is sent to specific employees when an abnormal consumption is detected during non-work days or during the night, for which no automation rule is possible.

From the data analysis, we found that air conditioning systems are one of the biggest energy consumers in the building, and standby power (measured during the night) makes up approximately 15% of the total amount of energy spent per day.

Figure 27, shows a daily view of energy consumptions by 2 different modes, linear and accumulated, which is useful for detecting the periods of the day when energy consumption increases or decreases relative to other days, and minimum and maximum consumption values recorded each hour, which are particularly useful for detecting anomalies and power limits.

In Figure 27, the chart on the left shows that it is possible to determine that the beginning of the day, lunch and afternoon is when more energy is spent, and on the second chart, it is possible to understand in which period of a certain day more energy than the average was spent, such as the day identified with a white arrow, such as at 16:00 hours where an extra 2.5 kilowatts hour was spent.

By knowing the maximum power usage per hour, it is possible to determine the necessary contracted power that also represents part of the energy bill.

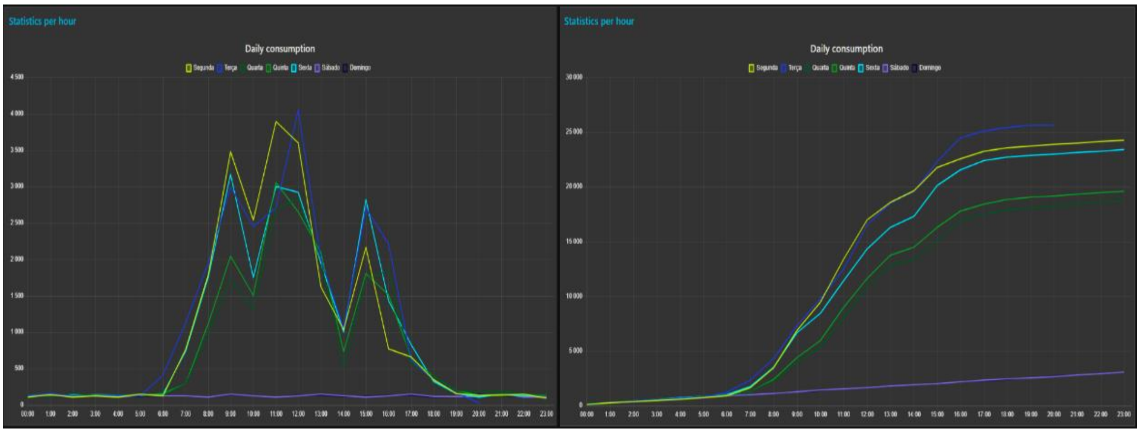
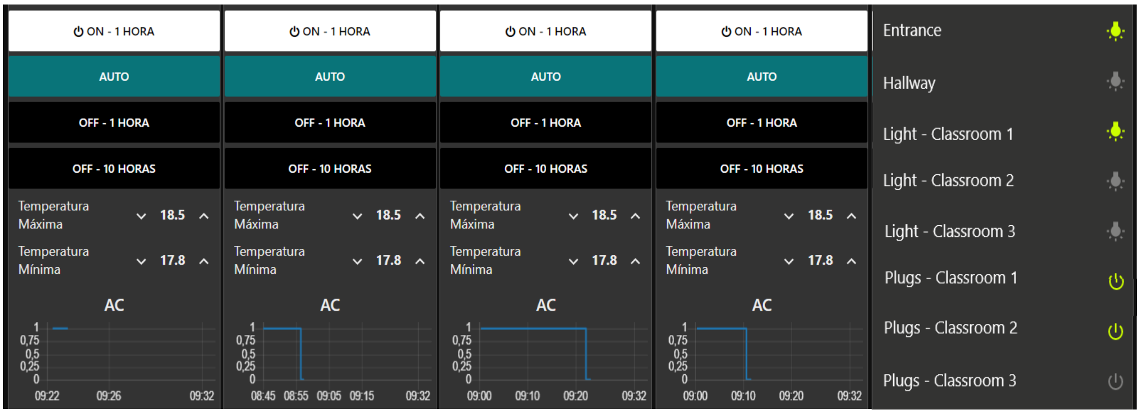


Figure 27 - Node-RED Dashboard, daily linear and cumulated consumption.

The dashboard interface, as mentioned before, includes interactive buttons and controllers, mainly for A/C and lighting control purposes. The A/Cs of each room can be turned On or Off from the dashboard remotely for 1 hour, or for the rest of the day. However, the default mode is AUTO, meaning, autonomous control based on sensor readings. The user can define a minimum and maximum temperature for the room to be used with the automatic rules. Ceiling lights and plugs can also be turned on or off from the dashboard, using the WiFi switches in Figure 28 as a bridge between the platform and the circuit itself.



Temperatura Máxima 18.5
Temperatura Mínima 17.8

Temperatura Máxima 18.5
Temperatura Mínima 17.8

Temperatura Máxima 18.5
Temperatura Mínima 17.8

Temperatura Máxima 18.5
Temperatura Mínima 17.8

Figure 28 - Node-RED Dashboard, A/C controllers (in Portuguese) and lights/plugs controllers.

A dedicated section (Figure 29) shows the time each room's A/C was on, allowing the user to understand which rooms require more heating or cooling per day.

On the bar chart, each color represents a different room A/C working time. By analyzing the data, we can observe that the last two days on the chart (01-04-2019 and 02-04-2019) only one room required heating. The room usually doesn't have more than five children inside because it is where they sleep when necessary, and this also explains why it required more heating than the others for every day during the previous week.

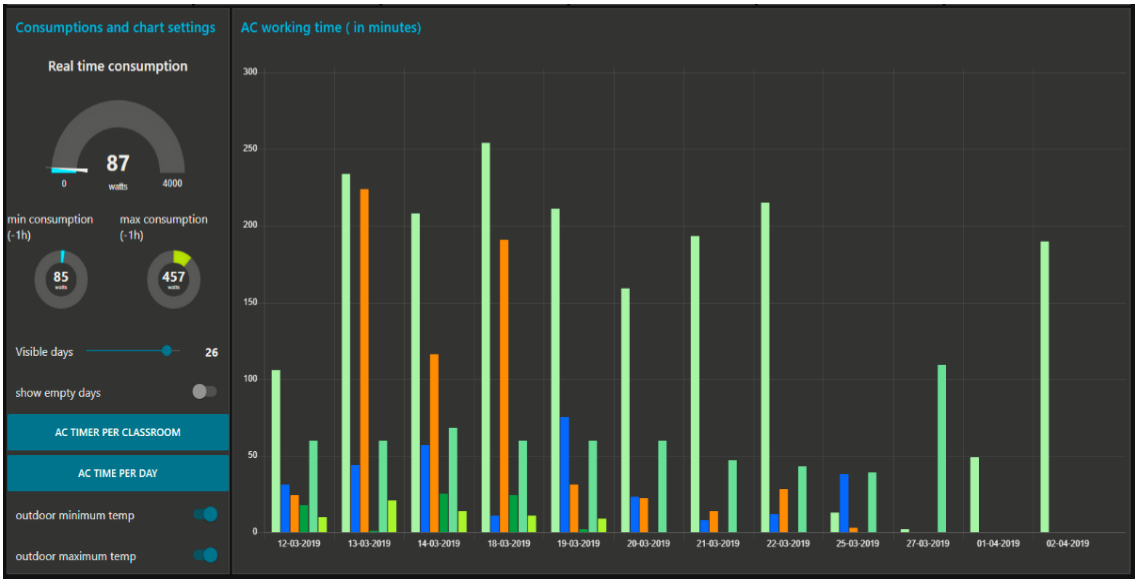


Figure 29 - Node-RED Dashboard, each color represents a different classroom A/C usage time in minutes.

It's also possible to compare the total amount of time of all A/Cs together, with the maximum and minimum expected temperatures for the District, and understand how outdoor temperature and general weather, affect indoor temperature and humidity and also daily consumption. Figure 30 shows another example of template 7 output, where for each day we show the:

- Sum of all rooms' A/Cs working time in hours;
- Total daily energy consumption;
- District minimum outdoor temperature;
- District maximum outdoor temperature.

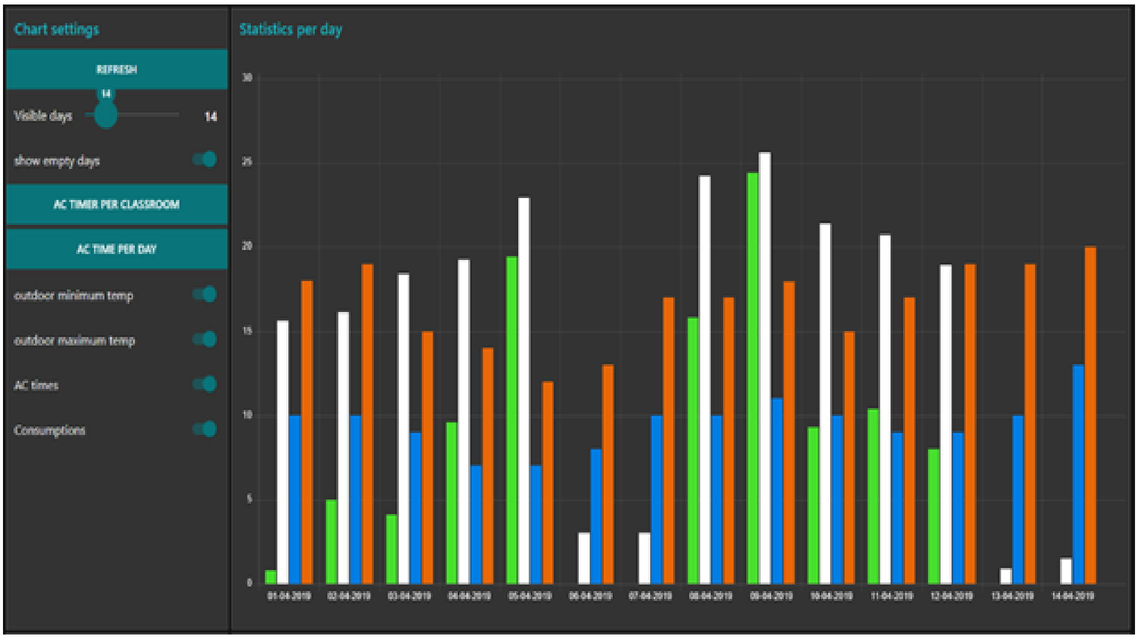


Figure 30 - Node-RED Dashboard, A/C usage time in hours vs outdoor temperatures vs daily energy consumption.

It is possible to observe a direct relation between outdoor temperatures and A/C usage, since when the temperature drops (02-04-2019 till 05-04-2019), A/C increases and the opposite occurs when the temperature rises (09-04-2019 till 14-04-2019). It is also possible to observe how much more energy is spent when A/Cs work for more time.

4.1.2. Saving Actions Outputs

Before the automation rules were created, all sensors data were observed for a week, to understand how temperature and humidity changed, considering the time of the day and outdoor temperatures. Users' templates allow us to create a big-picture overview, and from this, the local administrator used works using the definition of rules for automatic actions. We chose this user manual approach over data analytics because local users introduce a human perception about the environment that allows increasing savings. In this section, we show some examples of this.

As expected, during the night period, temperatures were lower at around 2–3 ° C, and humidity was lower at 10%–20% (Figure 31, created from template 2). During labor hours, the temperature would quickly rise in the morning when the A/Cs were turned on, then remain constant until closing hours when it begins to drop after the A/Cs were turned off. To keep a constant temperature on each room during the day, air conditioning systems remain on until being manually turned off, and despite the pre-set temperature on the remote, the real room temperature is 1 to 2 degrees above that of the remote, which proves the inefficiency of standard A/Cs' AUTO mode.

After the automation rules were implemented, the temperature behavior altered completely, changing from constant to a saw line type, (Figure 32), this is due to the established maximum and minimum temperatures that regulate each room's temperature according to these two limits. Besides limiting the temperature to a certain range, the system also prevents unnecessary usage when the room is empty, and because the amount of time it remains off is significant, the energy saved is reflected in the daily consumption.

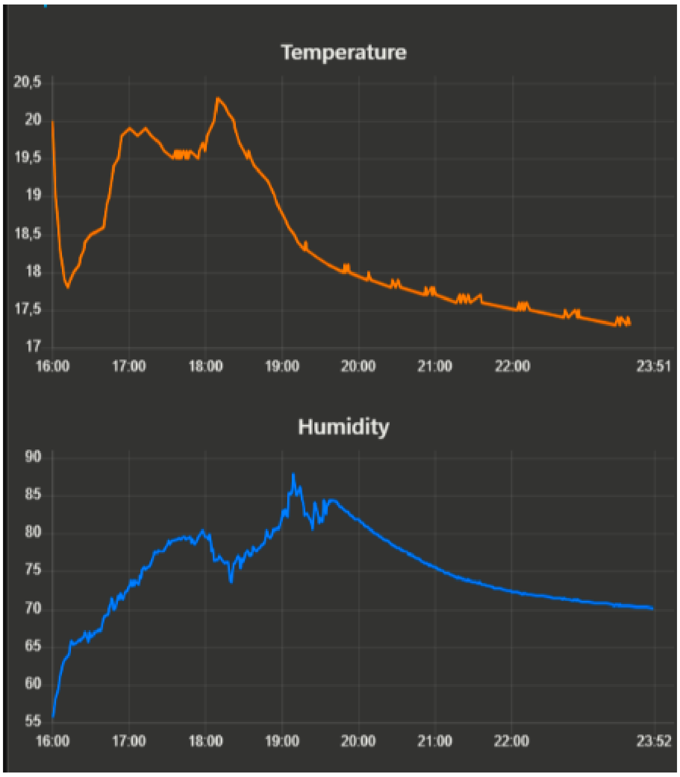


Figure 31 - Node-RED Dashboard, temperature variation overnight period.

The amount of time each room takes to lower 1 degree after the A/C is turned off, is directly proportional to the room size and inversely proportional to the room capacity during the day, meaning that a smaller room with fewer students cools down much faster and requires more heating and more often.

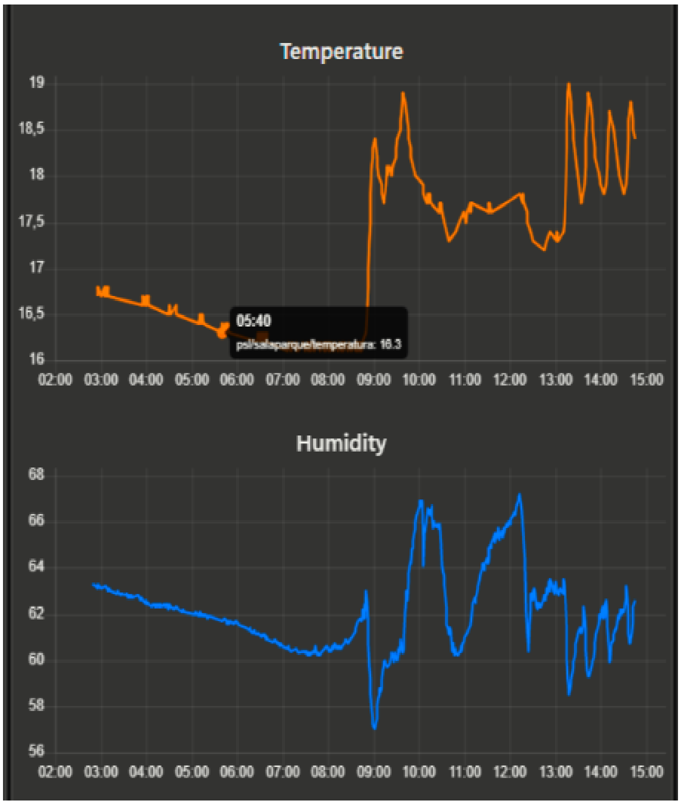
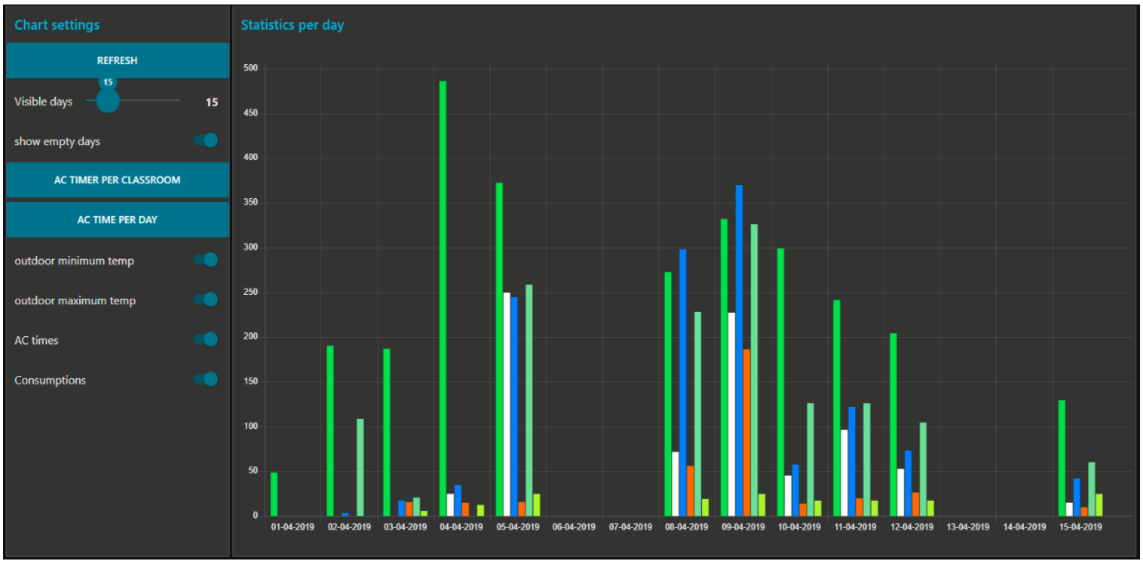


Figure 32 - Node-RED Dashboard, temperature variation during system operation.

This is perceived in the next graph, (Figure 33, created based on template 6), where the first column of each day representing the same room has more working time than all the others recurrently. This an example of an anomaly detected by interpretation of system data that allowed for discovering defective window isolation when during a rainy night, when the humidity all rooms were getting lower, while the humidity on a single classroom was showing the opposite behavior and getting higher. The interpretation of these facts allows the creation of rules to generate alerts and in some cases, trigger actions.

The room that presented the fastest temperature drop rate, on a windy day, began to display unusual A/C working times since it worked for hours straight without stopping. After a detailed analysis of the room, it was discovered that a pipe inside a decommissioned energy circuit board cabinet connected to the high ceiling where temperatures are much lower and there is much less isolation, causing the cold air from the street to flow down the pipe into the room. This room is presented in the next chart (Figure 33), as the first column of each day (green column).



Visible days 15

show empty days

outdoor minimum temp

outdoor maximum temp

AC times

Consumptions

Figure 33 - Node-RED Dashboard, A/C working time per room

Besides the anomalies mentioned above, another anomaly was detected multiple times, related to strange consumption values during the night or weekends, such as devices being left turned on when it was not expected, stand-by consumptions or malfunctioning appliances.

4.1.3. Energy Savings

Since 2016 when the energy monitoring system was implemented, and daily energy consumption during winter was on average 33 kWh, and daily energy consumption during Summer was 20 kWh on average, the knowledge about the consumption of the building allowed us to understand how energy consumption changes during the day and night times, and associate it with electric equipment who are responsible for most of the energy bill. Energy-saving policies were established and allowed a significant reduction in power usage and costs for the first months.

This reduction was followed by a stability period when it was apparently impossible to reduce power usage and costs even more. However, as soon as the LoRa system was created, another significant power consumption reduction took place.

As previously mentioned, the data analysis concluded that Kitchen appliances such as fridges or the dishwasher, and air conditioning systems were the main power consumers in the building, however with more precise data, the Node-Red dashboard allowed us to discover other cases where energy was being wasted. Doing an experiment with each circuit breaker at the main electrical switchboard the following standby power was detected:

- 3 circuit breakers powering an air conditioning unit each, and each of them had a persistent energy waste of 30 watts even with all units off, which meant 90 watts in total;
- Emergency lights with a persistent power consumption of 50 watts;
- Kitchen appliances such as the mosquito net spend 60 watts;
- Each computer and monitor spend 5 watts even if they are completely off.

All the referred power usage is considered to be waste during non-labor days, non-labor hours, which represents 50% of the day, or even more when there is no use during labor hours.

Using smart WiFi power sockets and a WiFi power socket for energy circuits, on each of these devices, and scheduling on and off timers, it's possible to save more than 3 kWh per day, which at the current energy price is equivalent to approximately €364 per year, more than 3 regular months of energy costs.

Figure 34 presents a monthly chart with the total energy consumption divided by the difference between 20 °C and the mean temperature of each month.

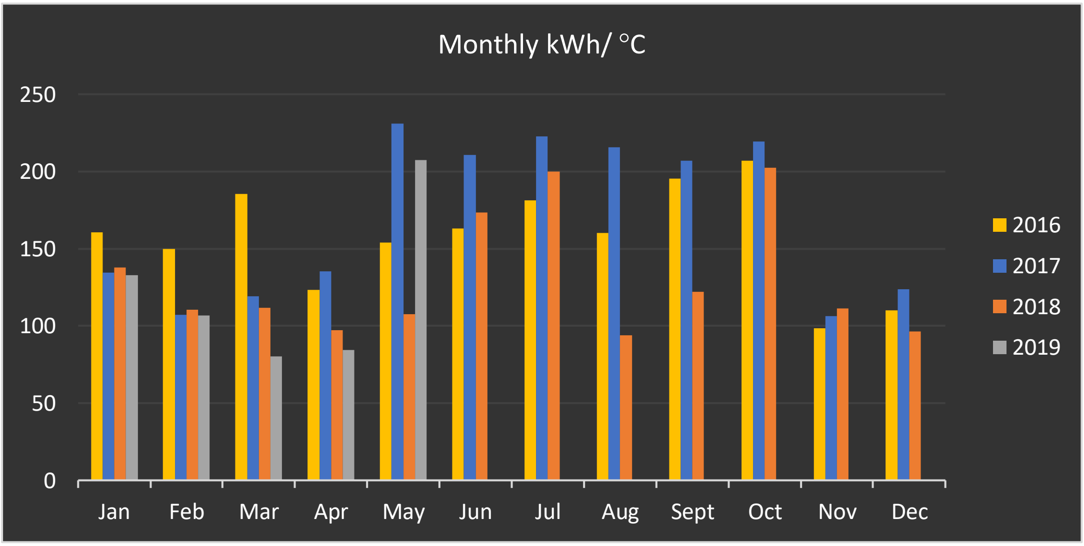


Figure 34 - Monthly energy consumption from October 2016 till May 2019, in kWh divided by a constant (20 °C) less the mean temperature of each month.

Since most parts of the system were implemented in February 2019 and the mean temperature increased during May 2019 (no A/C was required), the system effectiveness is only evident during March and April 2019.

4.1.4. Discussion

In 2016 the system was implemented, and successive improvements were performed based on the current approach of automatic saving actions based on the local working rules created by the local administrator based on personalized data visualization created by pre-defined templates. We introduced a novel MDA approach that provides automatic visualization personalized graphics to users that know the place but are not able to program. This easy approach to visualize collected data allows the creation of local heuristics to performs automatic saving actions on a regular basis. Another important factor is the LoRa communication (or similar low power long-range communication) that allows battery sensors to be placed across the building without the requirement of a power outlet or a power source replacement for a few years, and continuously provide reliable data, essential to apply sustainable and efficient measures. Since the project began, more than 750,000 sensor readings were taken and stored, including 150,000 temperature readings.

During the project, we were able to identify several anomalies within the building, such as poor window isolation, appliances left on during the night, missed usage of ceiling lights with enough natural light and many devices with unnecessary standby power consumption. We also detected a major improvement on each room’s temperature levels with the LoBEMS system running and resulting in energy savings.

In our case study shows in three years period, it was possible to save 3400 kWh (around €850) in a small building environment; taking into account the building tested area of 130 m^2, this gives a saving of €2.2/m^2 in a year. This solution applied to big scale building allows for even bigger savings.

Also, a real-time notification can be performed for email, SMS, or mobile device App to alert for unexpected behavior. This approach can be applied to any building from houses to companies and campus, provide a monitor control environment. In this IoT, Low Power and Long Range communication, like LoRa, play an important role since sensors can be easily installed without cables using internal batteries. For measurements every 5 min, the small solar panels can easily recharge the batteries during the day, even if the total charge is enough to keep the sensors running for several weeks.

This information visualized and correspondent actions in these three years, conduct to save around 20% to 25% of the total energy consumption, and investments were paid in the first year of operation. Another important finding that we detected is that the system's effectiveness at reducing energy consumption was continuously improving since the local administrator started to use it by himself. This was possible because Node-Red visualization templates enabled the modification of data visualization over time. Based on the available templates, variables and predefined charts, the administrator immediately started to changed heuristics and perfect the saving rules, by analyzing the provided indicators, as he intended, such as the chosen temperatures for each room, plugs schedules or warning employees about unsustainable behaviors detected with the system.

4.1.1. Application Costs

Considering that item three and five were purchased during 2016 in Stage 1, and the rest of the hardware was purchased for, and after the LoRa management system implementation, Stage 2 started in February 2019. The total project payback time is one year and seven months approximately; however, the LoRa system payback time is approximately ten months.

The project cost breakdown is described in Table 3, considering all the acquired hardware since 2016. We can estimate from these values an initial cost of €194 for the energy monitoring system and a cost of €63.3 per room, or €4.4/m^2 in total. Devices such as the LoRa gateway installed on the Raspberry Pi would not be necessary if the building was within the range of a LoRa antenna. If applied to facilities with bigger areas and more rooms, the project cost is expected to be significantly lower, since the LoRa approach allows the system to be easily scaled without further investments other than the sensor board itself.

Table 3 - Kindergarten application costs

Item	**Description**	**Price**
	Stage 1	
1	Energy Monitoring System	€194
2	4 x WiFi/Infra-red Emitters	€60
3	**Stage 2**	
	6 x (Sensors, microcontroller, battery and solar panel)	€124
4	Raspberry Pi with LoRa Hat	€100
5	4 x (WiFi Light switches and power sockets	€96
	Total	**€574**

4.2. Application Case at ISCTE Campus

In recent years, mobile devices allow researchers to collect data about human behavior using sensors embedded in these devices, in particular, a global positioning system (GPS), accelerometers, microphones, cameras and can be used as a fast interaction method approach.

This time, our system, together with mobile devices, creates a user interaction approach whose purpose is to warn and influence people to take actions, save energy, and work in a better environment.

In the current work, ISCTE-IUL's facility management office has been developing a BIM model that is being used to list rooms and locations, store materials information, and appliances data such as maintenance times. Building Information Modelling can be used to integrate this information in a format that can integrate all the referred data.

The BIM methodology depends on common, interoperable formats. In the current case, a BIM model of the campus is being developed by the campus Facilities Management team [25]. This model includes the complete geometrical description of the building, including all room’s names. The software used for the development of the BIM model was Autodesk’s Revit version 2019.

For this application case, the following goals were defined:

- Outdoor temperature and humidity sensors, distributed around each facade;
- Indoor temperature, humidity, light and motion sensors, at specific classrooms and administrative services;
- Temperature and humidity gradients built on the 3D model.
- Integration with existing BIM model using Unity;
- Historical visualization;

Outdoor Lansitec LoRa sensors were placed around the Campus, based on the sustainability and the architecture department of the university, to collect Temperature and Humidity values on all facades. The sensor's deployment map is presented in the next Figure 35.

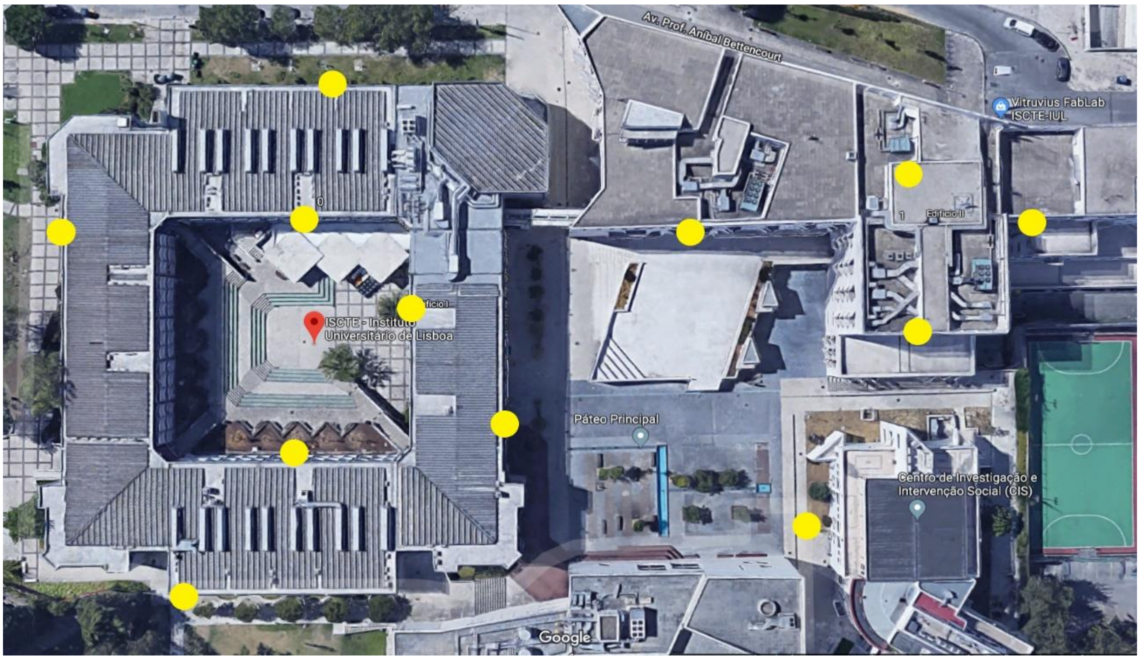


Figure 35 – Lansitec outdoor LoRa sensors deployment map

Each sensor is marked with a yellow circle, representing all 4 wings of Building I (on the left), and its interior atrium, the main atrium, a sensor placed on the rooftop above the Data Center, and around Building II (on the right).

4.2.1. Visualization tool

As previously mentioned, for visualization purposes, the model was imported to Unity and integrated with our system database, where the sensor's readings are stored. Each room’s temperature or humidity is displayed using color gradient functions, being red for higher temperatures, green for lower temperatures, dark blue for higher humidity values, and light blue for lower humidity values.

A simple 3D working model was first created to include individual objects, spheres for outdoor sensors, and volumes for indoor sensors (Figure 36), to represent a sensor’s location and collected data.

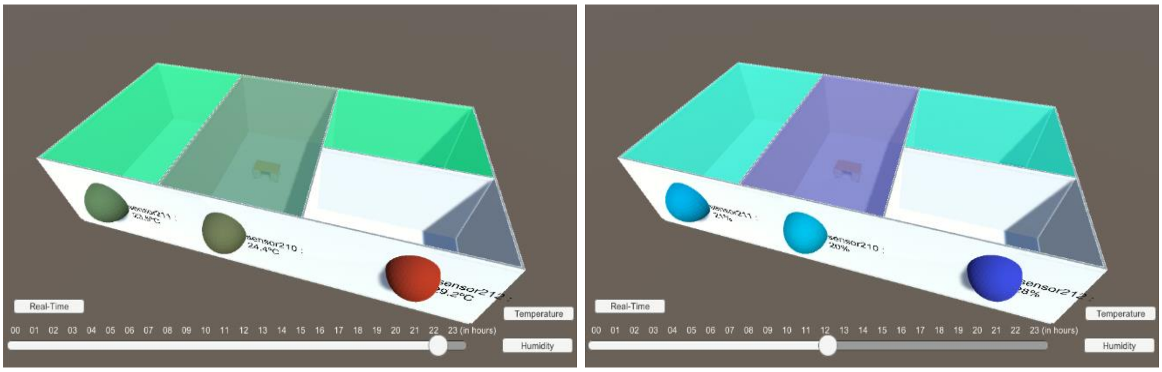


Figure 36 – 3D building imported from BIM model with indoor sensors as volumes and outdoor sensors as spheres

A more detailed UI was created to allow historical data to be displayed using a calendar element, and a time bar at the bottom of the screen (Figure 37). When time tools are not being used, data is updated in real-time. Besides the color gradient, a label indicates the sensor’s name and variable value.

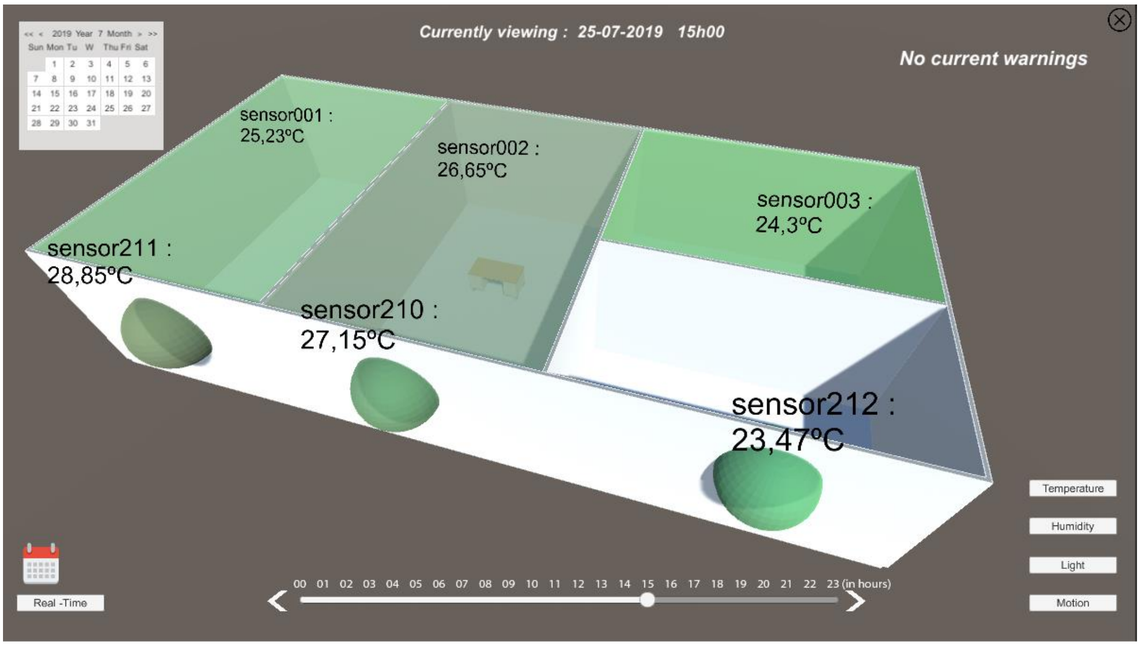


Figure 37 – 3D visualization tool with final UI elements

4.2.2. Discussion

After testing, a new 3D Model was imported, and sensors were placed at the University administrative services rooms, as presented in the next Figure 38. Indoor sensors were distributed according to blue circles, and the outdoor sensor as the red circle.

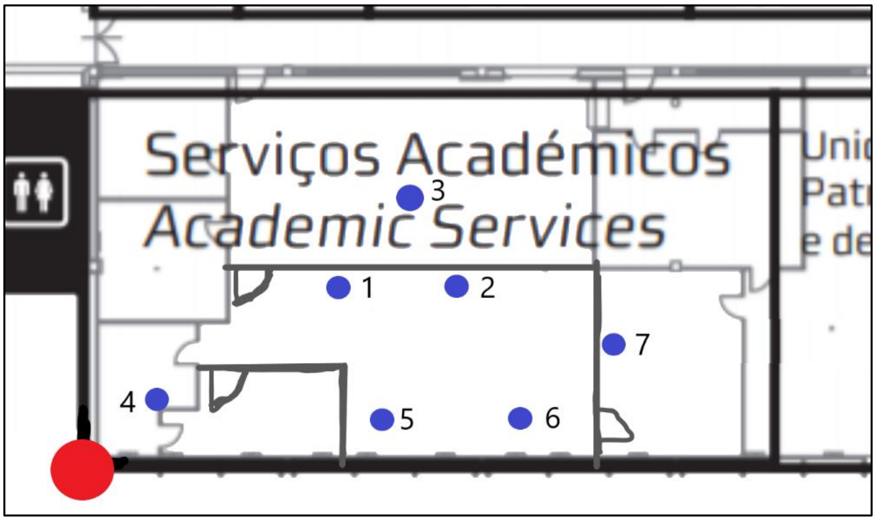
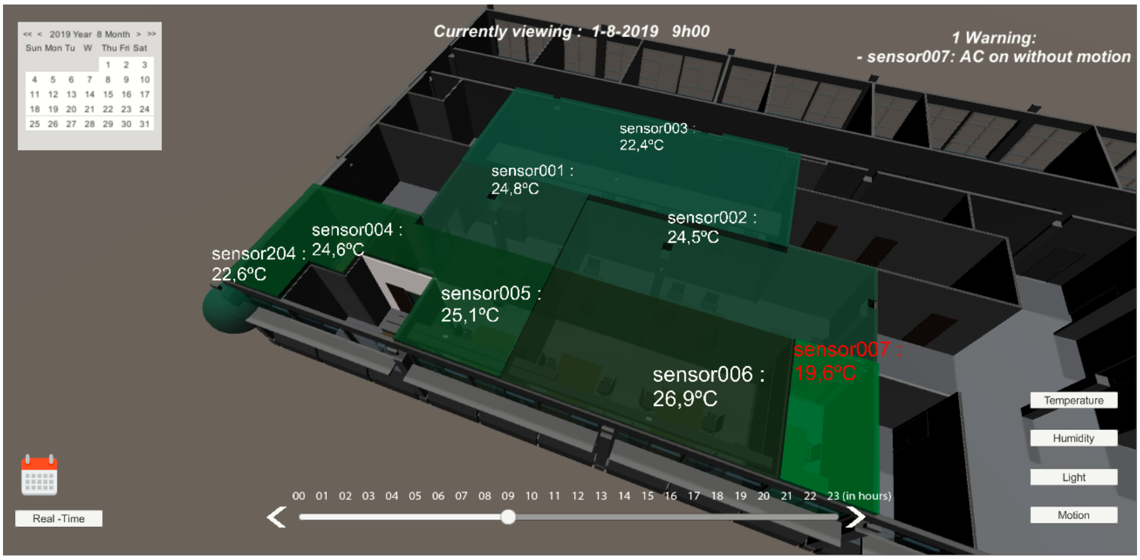


Figure 38 – ISCTE-IUL University Academic Services, indoor sensors placement marked with blue circles and outdoor sensor marked with red circle

On the main dashboard, users have several view modes for different variables, such as temperature, humidity, motion, and light. Each of the views presents a warning signal when an event is detected, related to that variable.

When the temperature mode is selected (Figure 39), each monitored room presents a color, related to the current temperature. If the current temperature is outside comfortable limits, the system displays a warning at the top right corner of the screen.

To prevent unnecessary energy wastes when ACs are working, and people are opening windows without knowing if the outdoor temperature is worse than the indoor temperature, each sensor module has a red LED that lights up when the outdoor temperature is greater than the indoor temperature during summer, and the opposite during winter. If this situation still happens, by comparing the latest indoor temperature readings, it is possible to determine an anomaly when the AC is on, and the temperature keeps rising, triggering an alert to the person in charge.



Currently viewing : 1-8-2019 9h00

1 Warning:
- sensor007: AC on without motion

Figure 39 – User interface with temperature mode selected for 01-08-2019 at 9:00h

Because the sensor007 room's temperature is much lower than outdoor temperature and adjacent rooms, the AC is determined as turned on, and because the motion sensor had a negative output for the past 5 minutes, the system displays a warning.

In the next Figure 40, the user interface presents relative humidity values for each sensor and creates a warning if any of the values are outside the comfort range.

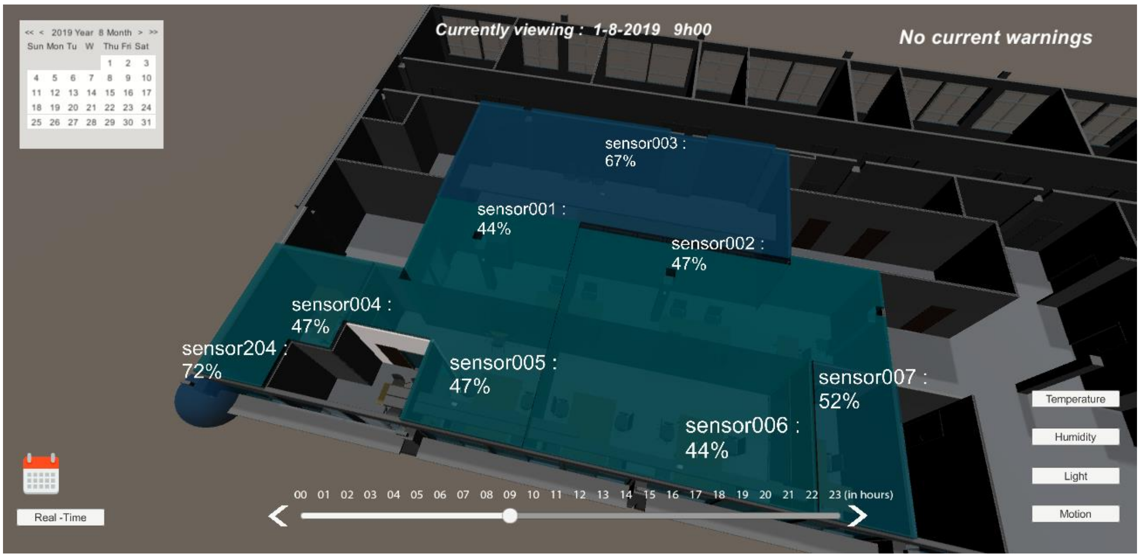


Figure 40 - User interface with temperature mode selected for 01-08-2019 at 9:00h

Another dashboard view mode is Light and motion, in which it is possible to observe the current light level determined by the light sensor and witch rooms have artificial light turned on (Figure 41).

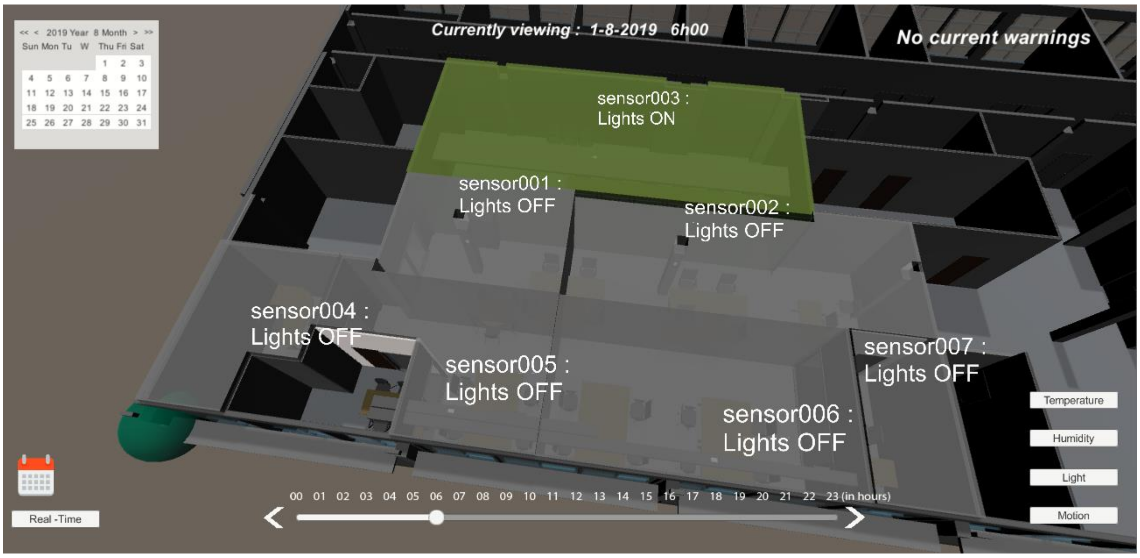


Figure 41 - User interface with light mode selected for 01-08-2019 at 6:00h

When the natural light level is considered enough, based on a previously made survey, if the system detects that artificial light has been turned on, it issues an alert to the 3D Model warning about the unnecessary energy waste.

This view is also where people can identify warnings about rooms with artificial light turned on, and no motion detected. If the motion sensor of the room doesn't detect movement for more than 5 minutes and light readings indicate that artificial light is on, a red warning is displayed on the 3D model, and it sends an email alert to the person in charge of that room.

After the system monitored the selected rooms for more than a month, we were able to detect more than 80 anomalies, being 30% related with artificial lights without any motion inside the rooms and the other 70% related with temperature warnings, considering that the system limits temperature warnings to 5 per day.

The general opinion of a few members of the university community was positive, and consider the system scalability to other rooms and buildings a good solution to reduce temperature problems during winter and summer seasons.

4.2.1. Application Costs

Our developed prototypes were used in this application case with the required sensors listed in the next Table 4.

Table 4 – ISCTE-IUL Campus application costs

Item	Description	Price
1	7 x LoRa microcontroller	€91
2	7 x DHT22 Temperature and humidity sensor	€63
3	7 x LiPo Batteries	€105
5	7 x 3D printed box	€70
6	Raspberry Pi	€50
	Total	€379

According to Table 4, a total of 379€ were spent on the ISCTE-IUL Campus application case, meaning a cost of 54.1€ per sensor box. Besides the indoor sensors, 12 outdoor sensors were placed around the campus to provide real-time outdoor readings that can be correlated with indoor readings after larger system deployment. Outdoor sensors represent an extra cost of 600€, however, the sensors the original battery can last up to 10 years.

4.3. Application Case at Datacenter

For the university proposed application case, the following goals were defined:

- High accuracy Temperature and Humidity monitoring;
- Battery-powered sensors to allow easy installation;
- Sensors enclosed into small and lightweight boxes;
- Web platform accessible to the Data Center staff from anywhere, at any time.

Data Center sensors were placed at specific points of interest, two of them on the newest server rack where most computing power is located, the other two on the older server rack, one at the telecommunications rack and one Control sensor located on the outer room, as presented in Figure 42.

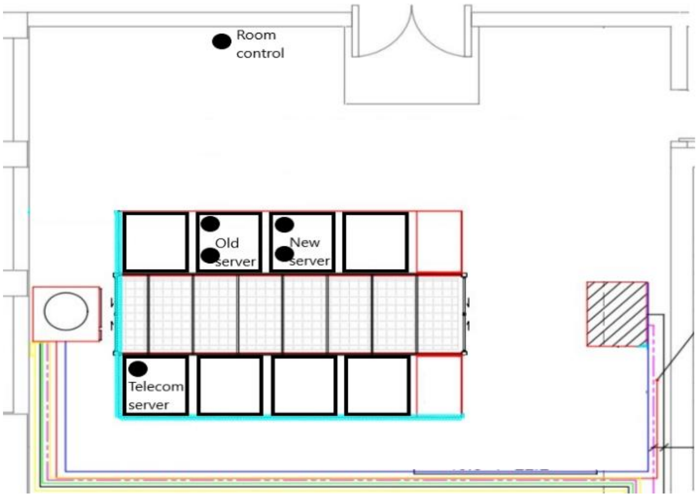


Figure 42 - Data Center sensors location

The sensors were placed to ensure that the airflow could pass through them, and the process was supervised by a Data Center technician (Figure 43).

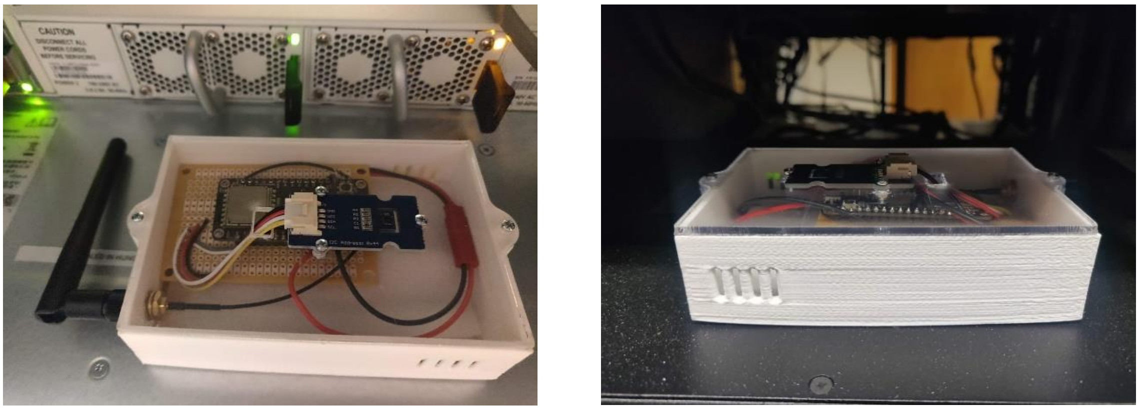


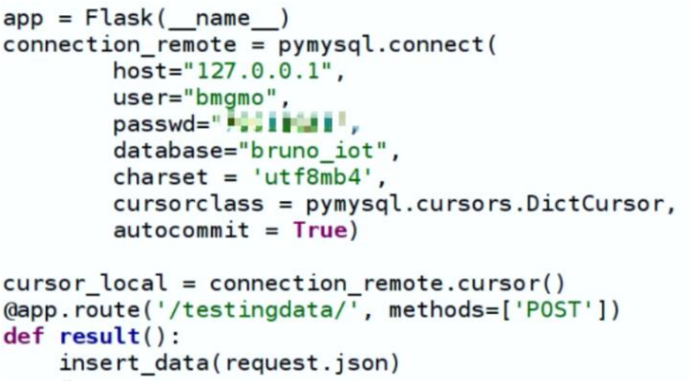
Figure 43 – Sensors placement on each server rack

After design, development, and implementation, the system ran for a month before any data pattern analysis was done, although, since it started gathering data, some issues were immediately detected. The dataset collected begins at 01/02/2019 and ends at 03/04/2019, after which some sensors started to run out of battery.

Since we had a LoRa network already implemented at the Data Center location, we developed an HTTP server to forward received LoRa packets from the CISCO LoRa network, mentioned on 3.2.2 – scenario 1, to our system Raspberry Pi.

This Web Server was created using a web framework named Flask, written in Python. After receiving an UPLINK message from the network Server (Actility), it creates an object according to the sensor type (once each sensor requires a different decoding process), sending it to the database running on the same Raspberry Pi.

The Web server setup is presented in Figure 44. Due to its simplicity, the Flask framework allows the creation of a Web server with very few lines of code, being the other ones, the connection with the local database.



```
app = Flask(__name__)
connection_remote = pymysql.connect(
        host="127.0.0.1",
        user="bmgmo",
        passwd="[redacted]",
        database="bruno_iot",
        charset = 'utf8mb4',
        cursorclass = pymysql.cursors.DictCursor,
        autocommit = True)

cursor_local = connection_remote.cursor()
@app.route('/testingdata/', methods=['POST'])
def result():
    insert_data(request.json)
```

Figure 44 - Flask Web server developed in Python

4.3.1. Data Visualization Reports

The dashboard developed from our system Templates 1 and 2, allows the user to quickly detect anomalies on a specific server rack based on the temperature and humidity gauges that display real-time information, as the daily temperature charts that can be toggled to humidity. It also allows the user to visualize historical data by using the time controls on the left, see Figure 45.

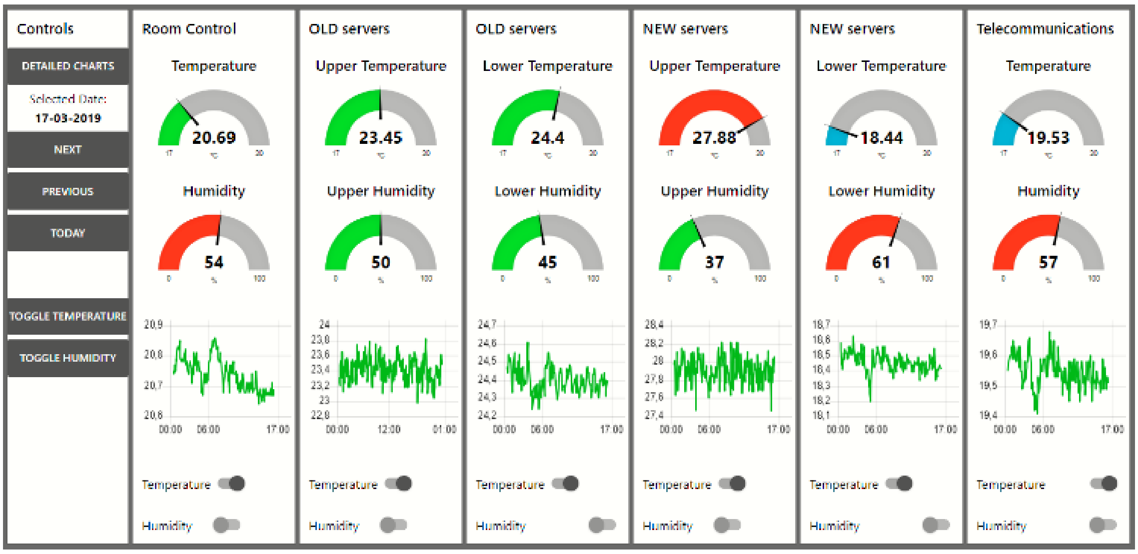


Figure 45 - Data Center Node-red template based dashboard

4.3.2. Discussion

One of the first detected discrepancies based on Template number 2 (Figure 46), would be the temperature difference inside the newest server rack where the sensor located at the upper shelf shows around 28°C while the lower shelf indicates 18°C, which provides us with a temperature variation of 10°C vertically.

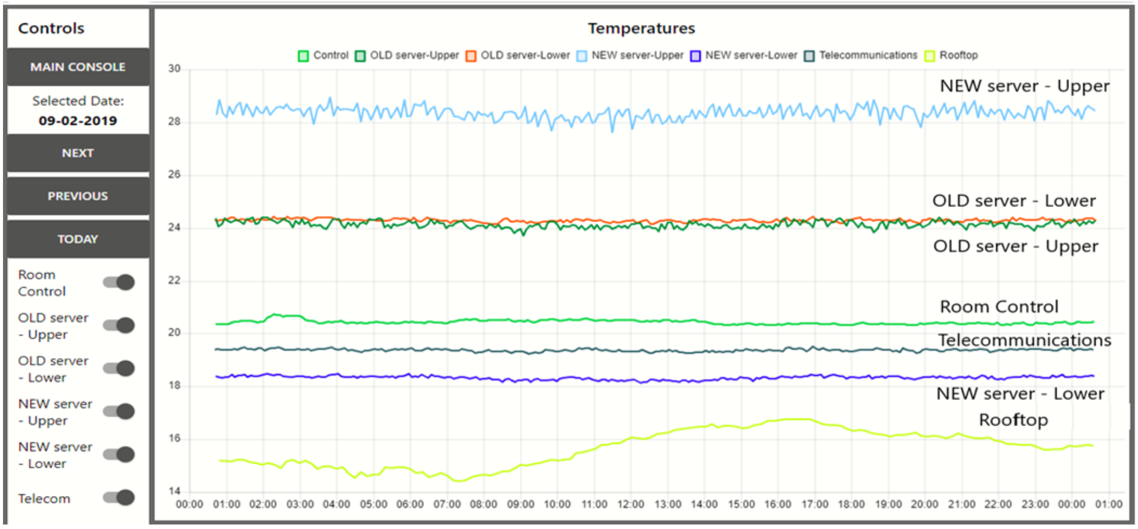


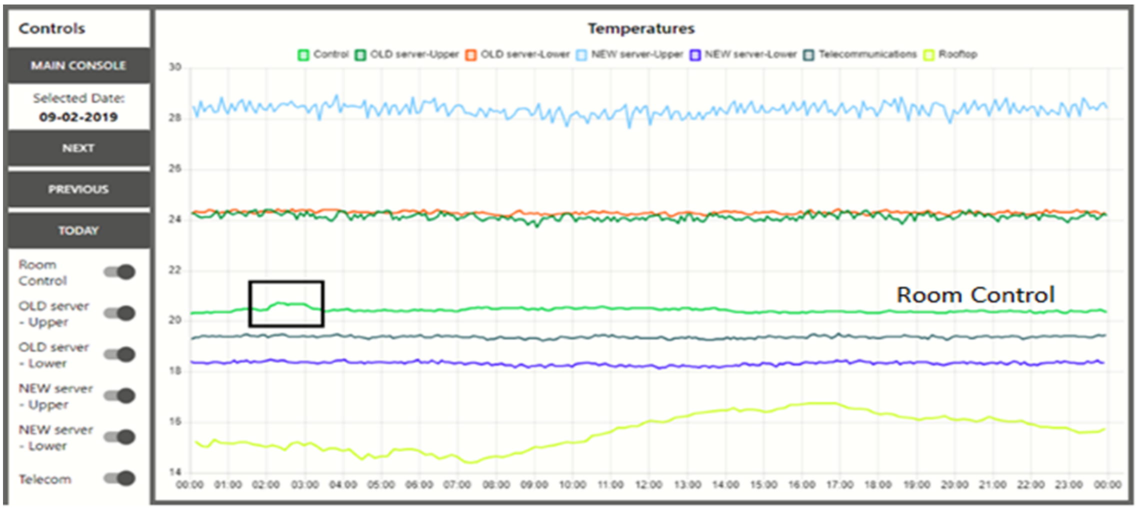
Figure 46 – Data Center temperature variation pattern of each sensor

This variation was always constant for the project duration, and it can be explained by the current computing load these servers currently have, and the rack occupation itself that is near 80% which means less cold air flowing between the hardware.

The temperature gradient inside the older server rack is less than 1°C, however, the sensor on the upper shelf detects a slightly lower temperature than the lower shelf as seen in Figure 46. Even if it seems contradictory, as the warmer air flows upwards, it can be explained by the rack occupation that is much lower than the newest rack and the upper shelves are almost empty which implies more airflow, sometimes colder than the temperature near the hardware on the lower shelf.

Figure 46 also shows that telecommunications servers have the lowest recorded temperatures with few or no fluctuations, and the room control sensor shows some fluctuations related to all the server's current load. For this project's time period and available data, no correlation between the rooftop above the data center and the room temperature was found.

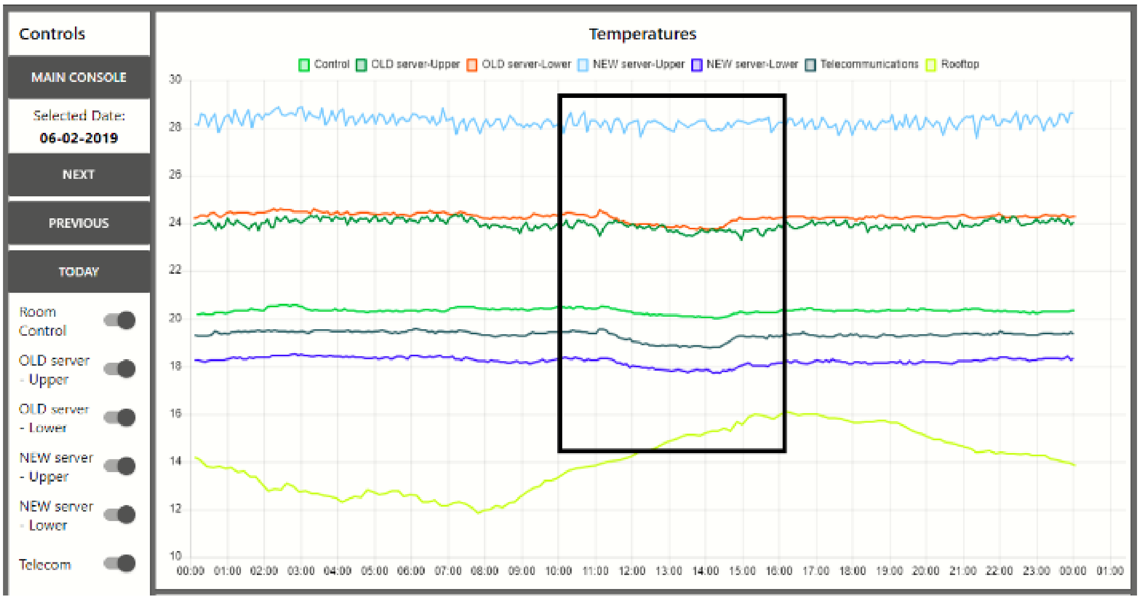
The anomaly in Figure 47, in the second chart, was detected every day except Sundays, and the variation itself of less than 1°C wasn't considered a problem as the temperature of all the other sensors remains unchanged, which means it is not caused by the air conditioning system, but the hardware itself that emits more heat from 2 am to 3 am and heats up the outer room slightly. This situation was discussed with the IT department, and the concluded cause was a daily backup routine.



Selected Date: 09-02-2019

Figure 47 – Data Center detected anomaly at 09/02/2019

The anomaly mentioned in Figure 48 on all sensors was detected through the project time period several times, but no pattern was found except for the duration of the anomaly and behavior. As it was detected on all sensors at the same time, it points to an air



Selected Date: 06-02-2019

Figure 48 – Data Center anomaly detected at 06/02/2019

conditioning response to a temperature spike preceding the anomaly or a malfunction with the air conditioning temperature sensor itself.

Humidity values presented in Figure 49, show that there wasn't any visible correlation between the humidity outside the building and inside the data center. Variations on these values were expected since humidity is related to temperature.

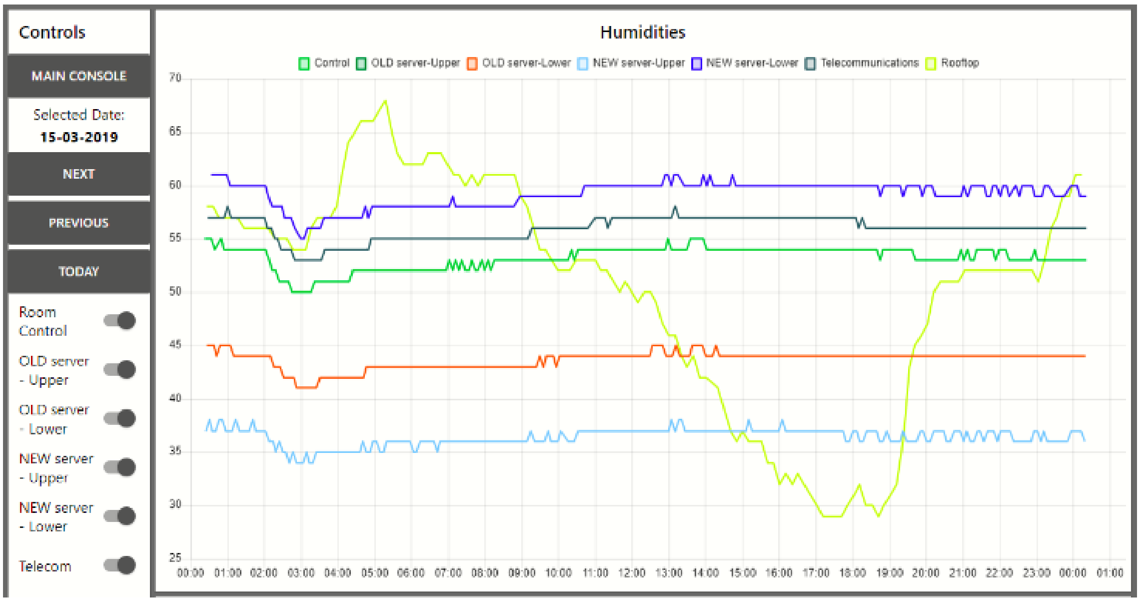
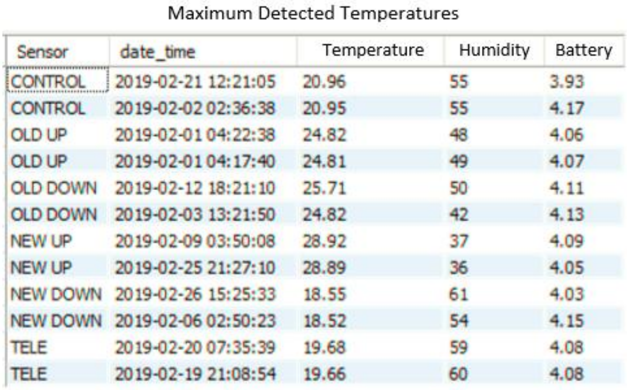

Selected Date: 15-03-2019

Figure 49 – Data Center humidity variation at 15/03/2019

Maximum detected temperatures correspond to early morning backup routines and minimum detected temperatures to 1 pm – 2 pm time period. From all sensors, both older and newer servers present bigger temperature variations of 2°C between maximum and minimum temperatures when room control and telecommunications server present only 1°C of maximum variation as proved by in Figure 50.



Maximum Detected Temperatures

Sensor	date_time	Temperature	Humidity	Battery
CONTROL	2019-02-21 12:21:05	20.96	55	3.93
CONTROL	2019-02-02 02:36:38	20.95	55	4.17
OLD UP	2019-02-01 04:22:38	24.82	48	4.06
OLD UP	2019-02-01 04:17:40	24.81	49	4.07
OLD DOWN	2019-02-12 18:21:10	25.71	50	4.11
OLD DOWN	2019-02-03 13:21:50	24.82	42	4.13
NEW UP	2019-02-09 03:50:08	28.92	37	4.09
NEW UP	2019-02-25 21:27:10	28.89	36	4.05
NEW DOWN	2019-02-26 15:25:33	18.55	61	4.03
NEW DOWN	2019-02-06 02:50:23	18.52	54	4.15
TELE	2019-02-20 07:35:39	19.68	59	4.08
TELE	2019-02-19 21:08:54	19.66	60	4.08

Figure 50 – Data Center maximum and minimum detected temperatures

4.3.3. Application Costs

All the hardware and software used to develop our sensor boxes were provided by ISCTE-IUL University and are listed in the next Table 5.

Table 5 – Data Center application costs

Item	Description	Price
1	6 x LoRa microcontroller	€78
2	6 x SHT31 Temperature and humidity sensor	€75.6
3	6 x LiPo Batteries	€90
5	6 x 3D printed box	€60
6	Raspberry Pi	€50
	Total	**€353.6**

According to Table 5, a total of 353.6€ were spent on the Data Center test case, meaning a cost of 59€ per sensor box. This price could easily be reduced if other choices were made for the sensor coverage since printing a 3D model is still not the cheapest solution. The temperature and humidity sensors were also one of the most expensive items used on this prototype due to the Data Center monitoring needs.

Chapter 5 - Conclusion and Future Work

In this research work, we developed a novel approach that helps administration entities to identify anomalies and create savings from personalized data visualization.

As the first main objective of this work, the full system implementation for small/medium size buildings, at the Kindergarten application case, presented a major impact on the indoor environment and electricity costs, due to our system savings. These saving actions were locally implemented with the definition of personalized heuristics, that are automatically applied based on the chosen templates. The infra-red technology used to interact with air conditioning (A/C) or heating systems, can be applied to a variety of other home equipment's that frequently use infra-red remotes. Plugs and light systems were controlled using cheap WiFi devices, integrated into our system. The collected data is manipulated to create an integrated view on dashboards, available for mobile devices.

Our developed system solution for BEMS has an installation cost of around €4.4 per square meter with custom features design for the user. LoRa allows easy installation because no cabling is involved, and real-time information, together with user behavior influence, plays an important role. Data visualization and data analytics are important for automation saving actions based on pre-defined rules. This node-red visualization templates can be reused and allow for local building administrators to configure and personalize data visualization in a similar MDA approach. This approach also allows the reduction of development costs since we can reuse parts of the prototypes and introduce more sensors based on the user needs.

Our three-year data set is available at [www.kaggle.com/brunomataloto/loems-lora] for scientific community usage. A/C units were turned on and off 3060 times when their usage was required or not required, and more than 130 kWh was saved, based on historical data. Besides all the improvements the system provided, both students' and employees' sense of comfort has increased.

From our ISCTE-IUL University Campus application case, we found that, at public places, where local administrator entities do not enroll in sustainability actions, the proposed approach also works, but it doesn't provide increasing savings through time. Because the system works partly based on initial performed configuration and also further user interactions to perfect the implemented rules, another approach was developed.

As our second major objective of this work, in large or public buildings, to overcome the previous limitation, we created the 3D BIM model approach as a bridge between system administrators and students. The overall perspective of the public is that the 3D model visualization tool can improve the students' work environment if applied on a larger scale. We are also working on a collaborative user approach, where local context real-time information is provided to users' mobile devices in a form that can influence them to perform saving actions.

The developed 3D visualization tool is easily introduced into different BIM models with other possible variables, such as an ongoing project at a Museum located in Lisbon, to display human occupation inside rooms and avoid crowds, by optimizing tour routes.

At the Data Center application case, we tested the developed prototypes as suggested, and encountered several anomalies in the room environment, based on the system visualization tools. Because a Data Center is a very important facility with very rigid rules, temperature, and humidity monitoring systems are commonly used. Existing systems cost is much higher, and the sensor's measurements are usually global, which reduced the chances to find abnormalities at individual servers. Our system can be easily deployed without extra costs and help reducing hardware failures and detect other events related to the room environment.

Our work was also used during the 2019 ISCTE's Summer School, to show and instruct students, during hands-on classes, how to develop an IoT system using LoRa.

This project also resulted in two scientific papers:

- Published in quartile one journal - Mataloto, B., Ferreira, J. & Cruz, N. (2019). LoBEMS - IoT for building and energy management systems. Electronics. 8 (7), 1-27
- Accepted for a conference - CCIoT in Japan 20-22 September 2019, Diogo Santos, Bruno Mataloto, João Carlos Ferreira, "Data Center Environment Monitoring System".
- Under development - Mataloto, B., Resende, J. & Ferreira, J. (2019). BIM models for IoT data representation

- Under development - Mataloto, B., Zecchini, M. & Ferreira, J. (2019). Sensors Can Change User Behavior?

We are also working this approach towards a prediction process and data presentation that can influence users towards pre-defined saving goals or defined energy standards. We think this approach adds additional features to this proposal and could be applied on shared space with a local interaction to users that do not administer the space, however, this kind of approach would be much more related with a user interface and user experience research project in order to influence behaviors.

To improve the 3D visualization tool, we are developing an actuation system to directly interact with University air conditioning systems at each classroom, allowing faster and automated management.

This project has also created the foundations for the Gulbenkian sustainability Project *“University Community Engagement in Technologies for Sustainability: a Social Architecture,* funded by the Calouste Gulbenkian Foundation, which aims to change people behavior at ISCTE-IUL University Campus. This project will use our developed LoRa IoT system together with other projects related to energy monitoring, to reduce energy consumption and increase overall sustainability.

The Gulbenkian sustainability Project will also be the starting point for my Ph.D. in Information Science and Technology.

Chapter 7 - References

[1] I. S. © O. 2014, “The world Bank -Electric power consumption (kWh per capita),” *2014*. [Online]. Available: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?name_desc=true. [Accessed: 24-Jul-2019].

[2] I. - International Energy Agency, “CO2 Emissions from Fuel Combustion 2018,” 2018, https://doi.org/10.1787/co2_fuel-2018-en.

[3] “CAT - Warming Projections Global Update December 2018 | Climate Action Tracker.” [Online]. Available: https://climateactiontracker.org/publications/warming-projections-global-update-dec-2018/. [Accessed: 21-Aug-2019].

[4] R. Sanchez-Iborra, J. Sanchez-Gomez, J. Ballesta-Viñas, M. D. Cano, and A. F. Skarmeta, “Performance evaluation of lora considering scenario conditions,” *Sensors (Switzerland)*, vol. 18, no. 3, p. 772, Mar. 2018, https://doi.org/10.3390/s18030772.

[5] M. Abo-Zahhad, S. M. Ahmed, M. Farrag, M. F. A. Ahmed, and A. Ali, “Design and implementation of building energy monitoring and management system based on wireless sensor networks,” *Proc. - 2015 10th Int. Conf. Comput. Eng. Syst. ICCES 2015*, pp. 230–233, 2016, https://doi.org/10.1109/ICCES.2015.7393051.

[6] N. H. Nguyen, Q. T. Tran, J. M. Leger, and T. P. Vuong, “A real-time control using wireless sensor network for intelligent energy management system in buildings,” *EESMS 2010 - 2010 IEEE Worskshop Environ. Energy, Struct. Monit. Syst. Proc.*, pp. 87–92, 2010, https://doi.org/10.1109/EESMS.2010.5634176.

[7] J. Byun, I. Hong, B. Kang, and S. Park, “Implementation of an adaptive intelligent home energy management system using a wireless ad-hoc and sensor network in pervasive environments,” *Proc. - Int. Conf. Comput. Commun. Networks, ICCCN*, pp. 1–6, 2011, https://doi.org/10.1109/ICCCN.2011.6005942.

[8] J. Han, C. S. Choi, W. K. Park, I. Lee, and S. H. Kim, “Smart home energy management system including renewable energy based on ZigBee and PLC,” *IEEE Trans. Consum. Electron.*, vol. 60, no. 2, pp. 198–202, 2014, https://doi.org/10.1109/TCE.2014.6851994.

[9] J. Wang, J. Huang, W. Chen, J. Liu, and D. Xu, “Design of IoT-based energy efficiency management system for building ceramics production line,” *Proc. 2016 IEEE 11th Conf. Ind. Electron. Appl. ICIEA 2016*, pp. 912–917, 2016, https://doi.org/10.1109/ICIEA.2016.7603712.

[10] M. Gao, Shaoliangshan, Huixiaowei, and Sunqingwei, “The system of wireless smart house based on GSM and ZigBee,” *2010 Int. Conf. Intell. Comput. Technol. Autom. ICICTA 2010*, vol. 3, pp. 1017–1020, 2010,

https://doi.org/10.1109/ICICTA.2010.118.

[11] C. V. J. Serra, D. Pubill, A. Antonopoulos, J. Serra, D. Pubill, A. Antonopoulos, and C. Verikoukis, “Smart HVAC control in IoT: Energy consumption minimization with user comfort constraints,” *Sci. World J.*, vol. 2014, p. 161874, Jun. 2014, https://doi.org/10.1155/2014/161874.

[12] K. F. Fong, V. I. Hanby, and T. T. Chow, “HVAC system optimization for energy management by evolutionary programming,” *Energy Build.*, vol. 38, no. 3, pp. 220–231, 2006, https://doi.org/10.1016/j.enbuild.2005.05.008.

[13] T. Lee, S. Jeon, D. Kang, L. W. Park, and S. Park, “Design and implementation of intelligent HVAC system based on IoT and Bigdata platform,” *2017 IEEE Int. Conf. Consum. Electron. ICCE 2017*, pp. 398–399, 2017, https://doi.org/10.1109/ICCE.2017.7889369.

[14] Y. T. Lee, W. H. Hsiao, C. M. Huang, and S. C. T. Chou, “An integrated cloud-based smart home management system with community hierarchy,” *IEEE Trans. Consum. Electron.*, vol. 62, no. 1, pp. 1–9, 2016, https://doi.org/10.1109/TCE.2016.7448556.

[15] E. Rodriguez-Diaz, J. C. Vasquez, and J. M. Guerrero, “Intelligent DC Homes in Future Sustainable Energy Systems: When efficiency and intelligence work together,” *IEEE Consum. Electron. Mag.*, vol. 5, no. 1, pp. 74–80, 2016, https://doi.org/10.1109/MCE.2015.2484699.

[16] N. Kushiro, S. Suzuki, M. Nakata, H. Takahara, and M. Inoue, “Integrated Residential Gateway Controller for Home Energy Management System,” *IEEE Trans. Consum. Electron.*, vol. 49, no. 3, pp. 629–636, 2003, https://doi.org/10.1109/TCE.2003.1233787.

[17] M. Erol-Kantarci and H. T. Mouftah, “Wireless sensor networks for cost-efficient residential energy management in the smart grid,” *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 314–325, 2011, https://doi.org/10.1109/TSG.2011.2114678.

[18] S. Stanley, “Harnessing Social Media,” *Ajr*, vol. 32, p. http://ajr.org/article?id=4860, 2010.

[19] K. Dittawit and F. A. Aagesen, “Home energy management system for electricity cost savings and comfort preservation,” *IEEE Int. Conf. Consum. Electron. - Berlin, ICCE-Berlin*, vol. 2015-Febru, no. February, pp. 309–313, 2015, https://doi.org/10.1109/ICCE-Berlin.2014.7034267.

[20] K. Buchanan, R. Russo, and B. Anderson, “Feeding back about eco-feedback: How do consumers use and respond to energy monitors?,” *Energy Policy*, vol. 73, pp. 138–146, Oct. 2014, https://doi.org/10.1016/j.enpol.2014.05.008.

[21] D. Vine, L. Buys, and P. Morris, “The Effectiveness of Energy Feedback for Conservation and Peak Demand: A Literature Review,” *Open J. Energy Effic.*, vol. 02, no. 01, pp. 7–15, 2013, https://doi.org/10.4236/ojee.2013.21002.

[22] P. Petkov, S. Goswami, F. Köbler, and H. Krcmar, “Personalised eco-feedback as

a design technique for motivating energy saving behaviour at home," in *NordiCHI 2012: Making Sense Through Design - Proceedings of the 7th Nordic Conference on Human-Computer Interaction*, 2012, pp. 587–596.

[23] J. Froehlich, L. Findlater, and J. Landay, "The design of eco-feedback technology," in *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10*, 2010, p. 1999.

[24] A. Coskun, J. Zimmerman, and C. Erbug, "'Corrigendum to "Promoting sustainability through behavior change: A review" [Design Studies Volume 41 (Part B) (November 2015) pp. 183–204],'" *Des. Stud.*, vol. 42, pp. 140–149, Jan. 2016, https://doi.org/10.1016/j.destud.2015.12.001.

[25] J. Ferreira, H. Martins, M. Barata, V. Monteiro, and J. L. Afonso, "OpenADR—Intelligent electrical energy consumption towards internet-of-things," in *Lecture Notes in Electrical Engineering*, 2017.

[26] J. Ferreira and A. Martins, "Building a Community of Users for Open Market Energy," *Energies*, vol. 11, no. 9, p. 2330, Sep. 2018, https://doi.org/10.3390/en11092330.

[27] C. M. Eastman, *BIM handbook : a guide to building information modeling for owners, managers, designers, engineers, and contractors*. Wiley, 2008.

[28] A. K. Nicał and W. Wodyński, "Enhancing Facility Management through BIM 6D," *Procedia Eng.*, vol. 164, pp. 299–306, 2016, https://doi.org/10.1016/j.proeng.2016.11.623.

[29] C. M. Bojić, S. Djordjević, A. Stefanović, M. Miletić, *Decreasing energy consumption in thermally non-insulated old house via refurbishment," Energy and Buildings*, 54 ,pp. 50. 2012.

[30] R. Resende, L. Coroado, A. L. Lopes, R. Sacadura, M. H. Teixeira, S. Eloy, and J. Dias, "Plataforma Web-BIM para Gestão de Instalações de um Campus Universitário," in *1º Congresso Português de Building Information Modelling*, 2016, no. November, pp. 501–511.

[31] N. El-Sayed, I. Stefanovici, G. Amvrosiadis, A. A. Hwang, and B. Schroeder, "Temperature management in data centers: Why some (might) like it hot," in *Proceedings of the 12th ACM SIGMETRICS/PERFORMANCE Joint International Conference on Measurement and Modeling of Computer Systems (SIGMETRICS '12)*, 2012.

[32] A. Rawson, J. Pfleuger, and T. Cader, "Data Center Power Efficiency Metrics: PUE and DCiE," *Green Grid*, 2007.

[33] R. Miller, "Google: Raise your data center temperature." [Online]. Available: https://www.datacenterknowledge.com/archives/2008/10/14/google-raise-your-data-center-temperature/. [Accessed: 23-Dec-2018].

[34] H. Company, "Improve and Maximize Efficiency as You Save Money." [Online]. Available:

http://www.hp.com/hpinfo/newsroom/press_kits/2009/ecosolutions/reduceimpact/Whitepaper-datacenter_improvements.pdf. [Accessed: 08-Sep-2019].

[35] S. Saha and A. Majumdar, "Based Wireless Sensor Network and Cloud Based Dashboard with Real Time Alert System," *2017 Devices Integr. Circuit*, pp. 23–24, Mar. 2017, https://doi.org/10.1109/DEVIC.2017.8073958.

[36] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," *ICT Express*, 2019, https://doi.org/10.1016/j.icte.2017.12.005.

[37] J. S. Lee, Y. W. Su, and C. C. Shen, "A comparative study of wireless protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *IECON Proceedings (Industrial Electronics Conference)*, 2007.

[38] H. Pihkola, M. Hongisto, O. Apilo, and M. Lasanen, "Evaluating the energy consumption of mobile data transfer-from technology development to consumer behaviour and life cycle thinking," *Sustain.*, vol. 10, no. 7, Jul. 2018, https://doi.org/10.3390/su10072494.

[39] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low Power Wide Area Networks: An Overview," *IEEE Commun. Surv. Tutorials*, vol. 19, no. 2, pp. 855–873, 2017, https://doi.org/10.1109/COMST.2017.2652320.

[40] Y. P. E. Wang, X. Lin, A. Adhikary, A. Grövlen, Y. Sui, Y. Blankenship, J. Bergman, and H. S. Razaghi, "A Primer on 3GPP Narrowband Internet of Things," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 117–123, Jun. 2017, https://doi.org/10.1109/MCOM.2017.1600510CM.

[41] C. McClelland, "IoT Connectivity - Comparing NB-IoT, LTE-M, LoRa, SigFox, and other LPWAN Technologies | IoT For All," *iotforall*, 2018. [Online]. Available: https://www.iotforall.com/iot-connectivity-comparison-lora-sigfox-rpma-lpwan-technologies/. [Accessed: 01-Oct-2019].

[42] Seeed, "Seeeduino LoRaWAN - Seeed Wiki." [Online]. Available: http://wiki.seeedstudio.com/Seeeduino_LoRAWAN/. [Accessed: 25-Aug-2019].

[43] "WIFI LoRa 32 (V2) – Heltec Automation." [Online]. Available: https://heltec.org/project/wifi-lora-32/. [Accessed: 25-Aug-2019].

[44] "LoRa32u4 II Lora LiPo Atmega32u4 SX1276 HPD13 868MHZ EU Antenna." [Online]. Available: https://bsfrance.fr/lora-long-range/1345-LoRa32u4-II-Lora-LiPo-Atmega32u4-SX1276-HPD13-868MHZ-EU-Antenna.html. [Accessed: 25-Aug-2019].

[45] D. E. Henton, P. Gruber, J. Lunt, and J. Randall, "Polylactic acid technology," in *Natural Fibers, Biopolymers, and Biocomposites*, 2005.

[46] LoRa Alliance, "LoRaWAN 1.0.3 specification," *lora-alliance.org*, no. 1 [Online], Accessible: https://lora-alliance.org/sites/default/files/2018-07/lorawan1.0.3.pdf, pp. 1–72, 2018, https://doi.org/10.1016/j.wneu.2012.09.021.

[47] K. Feichtinger, Y. Nakano, K. Fukushima, and S. Kiyomoto, “Enhancing the Security of Over-The-Air-Activation of LoRaWAN Using a Hybrid Cryptosystem,” *IJCSNS Int. J. Comput. Sci. Netw. Secur.*, vol. 18, no. 2, pp. 1–9, 2018.

[48] Enertiv, “4 Limitations of Building Management System (BMS) Data,” *Enertiv,* 2018. [Online]. Available: https://www.enertiv.com/resources/blog/4-limitations-bms-data. [Accessed: 25-Jun-2019].

[49] “The Things Network,” *LoRaWAN Overview*, 2019. [Online]. Available: thethingsnetwork.org. [Accessed: 27-Jul-2019].

[50] Object Management Group, “Model Driven Architecture (MDA) | Object Management Group,” 2019. [Online]. Available: https://www.omg.org/mda/. [Accessed: 08-Jul-2019].

[51] B. Ozarisoy, H. Altan, B. Ozarisoy, and H. Altan, “Adoption of Energy Design Strategies for Retrofitting Mass Housing Estates in Northern Cyprus,” *Sustainability*, vol. 9, no. 8, p. 1477, Aug. 2017, https://doi.org/10.3390/su9081477.

[52] B. Ozarisoy and H. Elsharkawy, “Assessing overheating risk and thermal comfort in state-of-the-art prototype houses that combat exacerbated climate change in UK,” *Energy Build.*, vol. 187, pp. 201–217, Mar. 2019, https://doi.org/10.1016/J.ENBUILD.2019.01.030.