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Développement d'un système innovant pour les bâtiments intelligents : Application au confort des usagers et efficacité énergétique

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PhD Thesis in Cotutelle

Between

University of Lille

&

Mohammed V University of Rabat - Mohammadia School of Engineering

To obtain the degrees of :

Doctor in Science and Engineering Techniques of the Mohammadia School of Engineering

&

Doctor of the University of Lille

Civil Engineering

Presented by :

Lamine LAGSAIAR

Civil Engineering and Geo-Environment Laboratory

&

Laboratory of Systems Analysis, Information Processing and Industrial Management

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Development of an innovative system for smart buildings: Application to user comfort and energy efficiency

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Defended publicly in Lille on 05/11/2021 before the jury composed of :

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This thesis is dedicated

To my parents, who made me the man I am today

In memory of Lahbib, Saleh, Jmaiaa and Salka, my grandparents, Peace to their souls!

To my brothers and sisters, who have supported me throughout my career

In memory of Said and Mouloud, my uncles, Peace to their souls!

To my grandmother, my uncles, my aunts, my cousins and my entire family.

To my friends, classmates, and everyone who has helped me in any way to get to where I am today.

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Abstract

This thesis presents new developments in the design of a smart building system that can supervise energy consumption in buildings and indoor comfort conditions. This system was used to investigate the impact of indoor comfort in classrooms on the learning capacity of students and the analysis of energy efficiency and indoor comfort condition in social housing units.

The thesis is composed of three parts.

The first chapter presents the methodology of the thesis. It presents the architecture and construction of a novel smart building system that could monitor and control buildings' use safely and optimally and could be easily used in buildings' management. It includes nine modules that inter-communicate. The methodology also presents the software architecture IoT used for the building monitoring and this system to manage fifteen social housing units during a year.

The second chapter analyzes the impact of the indoor classroom environment on students' learning efficiency, which is based on smart classroom monitoring and a questionnaire about the students' assessment of the comfort conditions and learning efficiency. Multi-sensor devices measure the indoor temperature, relative humidity, and CO2 concentration at the students' desks. Data analysis concerned an investigation of the spatial and temporal variation of the comfort parameters and their correlation with students' assessment of comfort conditions and learning efficiency.

The third chapter investigates how smart monitoring of social housing units helped understand energy consumption and indoor comfort. The experiment is based on monitoring 13 social housing in the North of France. The monitoring included indoor comfort (temperature and humidity), the total energy consumption, and the energy consumed for heating, hot water, and lighting. It also had hot water consumption.

Résumé

Cette thèse présente de nouveaux développements dans la conception d'un système de bâtiment intelligent qui peut superviser la consommation d'énergie dans les bâtiments et les conditions de confort intérieur. Ce système a été utilisé pour étudier l'impact du confort intérieur dans les salles de cours sur la capacité d'apprentissage des élèves et l'analyse de l'efficacité énergétique et des conditions de confort intérieur dans les logements sociaux.

La thèse est composée de trois chapitres.

Le premier chapitre présente la méthodologie de la thèse. Il détaille l'architecture et la construction d'un nouveau système de bâtiment intelligent qui pourrait surveiller et contrôler l'utilisation des bâtiments de manière sûre et optimale et pourrait être facilement utilisé dans la gestion des bâtiments. Le système comprend neuf modules qui communiquent entre eux. La méthodologie présente également l'architecture logicielle IoT utilisée pour la surveillance des bâtiments et ce système pour gérer une quinzaine de logements sociaux pendant une année.

Le deuxième chapitre analyse l'impact de l'environnement intérieur dans des salles de cours sur l'efficacité d'apprentissage des étudiants. La recherche est basée sur une surveillance intelligente de la classe et un questionnaire sur l'évaluation par les étudiants des conditions de confort et d'efficacité de l'apprentissage. Des systèmes multi-capteurs mesurent la température intérieure, l'humidité relative et la concentration de CO_2 sur les bureaux des étudiants. L'analyse des données a porté sur la variation spatiale et temporelle des paramètres de confort et leur corrélation avec les conditions de confort et d'efficacité de l'apprentissage perçues par les étudiants.

Le troisième chapitre examine comment la surveillance intelligente des logements sociaux a aidé à comprendre la consommation d'énergie et le confort intérieur. L'expérimentation repose sur le suivi de 13 logements sociaux dans le Nord de la France. La surveillance comprenait le confort intérieur (température et humidité), la consommation totale d'énergie et l'énergie consommée pour le chauffage, l'eau chaude et l'éclairage. Il a comporté aussi le suivi de la consommation d'eau chaude.

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List of Abbreviations

Iot: internet of things.

WSN: Wireless sensor network

API: Application Programming Interface

CSS: Cascading Style Sheets

HTML: Hypertext Markup Language

PHP: Hypertext Preprocessor

HTTP: Hypertext Transfer Protocol

ICT: Information and Communication Technologies

LTE: Long-Term Evolution

RFID: Radio Frequency Identification

SQL: Structured Query Language

RF : Radiofrequency

SVI: spatial variation index

General Introduction

According to Eurostat, the building sector is responsible for 40% of the world's energy consumption and contributes 30% of total CO_2 emissions (P. H. Shaikh et al. 2014). The European Union has set long-term targets to improve energy efficiency and reduce greenhouse gas emissions by 90% by 2050 (European Commission).

These challenges have driven the building sector to seek new solutions and technologies to ensure energy efficiency and healthy environments for occupants and provide services and tools to encourage occupants to be part of the solution.

Recent development in digital technology, particularly the Internet of Things and Artificial intelligence, resulted in developing a new area of technology called smart Technology. This new technology has proved to be effective in improving the efficiency, security, and services for various urban systems, including buildings (Smart Building), infrastructure (Smart Infrastructure), mobility (smart mobility), and governance (Smart Governance).

For several years, the concept of smart buildings has attracted the interest of researchers, governments, and companies because of its promising objectives to achieve energy efficiency and indoor comfort for occupants. The Intelligent Building Institute of the United States defined the concept of intelligent building in 1989 as a building that provides an efficient environment through the optimization of systems, structures, management, services, and interrelationships between them (Apanaviciene, R et al. 2020). Recently, several definitions have been introduced to characterize smart buildings. But up to now, the concept and characteristics of smart buildings are still not defined singly and straightforwardly (Al Dakheel et al. (2020)). The smart building concept can have many different meanings and aspects depending on the research context and its use. In the context of this research, the term smart refers to the use of smart sensors and smart actuators for buildings' survey and control to improve the buildings' energy efficiency and indoor comfort.

This research is based on experiments conducted in different buildings to study comfort conditions and energy consumption. We developed an intelligent building system with a novel software architecture to monitor comfort conditions and energy consumption and control building equipment. Furthermore, we investigated the use of intelligent monitoring and user feedback to study the impact of the indoor environment on learning efficiency in classrooms. We have also conducted an experimental analysis of indoor environmental quality and energy consumption in social housing units.

This dissertation is organized into 3 chapters:

The first chapter presents the methodology of the thesis. It presents the architecture and construction of a novel smart building system that could monitor and control buildings' use safely and optimally and could be easily used in buildings' management. It includes nine modules that inter-communicate. The methodology also presents the software architecture IoT used for the building monitoring and this system to manage fifteen social housing units during a year.

The second chapter analyzes the impact of the indoor classroom environment on students' learning efficiency, which is based on smart classroom monitoring and a questionnaire about the students' assessment of the comfort conditions and learning efficiency. Multi-sensor devices measure the indoor temperature, relative humidity, and CO2 concentration at the students' desks. Data analysis concerned an investigation of the spatial and temporal variation of the comfort parameters and their correlation with students' assessment of comfort conditions and learning efficiency.

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1 Chapter 1: Methodology: Conception of a smart building monitoring system

This chapter was published as a research paper in the International Journal Sensors (FI 3.57). Link : https://www.mdpi.com/1424-8220/21/17/5810.

1.1 *Introduction*

This chapter is devoted to the research methodology. It presents the architecture and the design of a novel smart building system which aims to provide a new solution of monitoring and control of the buildings respecting the different layers of the smart buildings and its interactions. The chapter begins with a general description of the smart building architecture layers. Then, we present each layer of this system.

Scholars tackled different topics related to the conception of smart building monitoring system. Alexakis et al. (2019) used a natural language processing to control and monitor sensors. They relied on the integration of several third-party APIs such as the Dialogflow API and open-source technologies that aim to develop new and very fast smart building solutions. They choose Wemos D1 Mini V3 as microcontrollers with integrated Wifi chip onboard. Lin et al (2019) used Nodemcu as microcontrollers and Raspberry Pi as Gateway. Balikhina et al. (2017) used Intel Edison development platform as a gateway that use MQTT as a protocol of communication similar to that proposed by Alexaki et al. (2019).

Rihab et al. (2020) investigated IoT security and privacy in smart buildings. They presented an unprecedented contribution by offering a login module to manage user registration and login operations more securely using a multi-factor authentication method based on a password, liveliness detection, and facial recognition. Chen et al. (2009) proposed architecture for an intelligent building control system to improve the energy efficiency of buildings with a proof-of-concept implementation. Dutta et al. (2017) presented a solution based on fog and cloud architecture that uses open-source software to reduce costs without compromising the system's quality of service. On the other hand, Al-Ali et al. (2017) proposed a smart home system based on IoT-Big data to manage energy consumption using remote monitoring and control through a mobile application. Bellagente et al. (2015), Ock et al. (2016), and Uribe et al. (2015) proposed solutions for energy management, but they did not present the software architecture of these systems. Few researchers tackled smart building gateways. Yan et al. (2020) compared recent smart gateways used in smart buildings. The comparison was based on the operating systems, wireless communication protocols, and security.

The literature misses papers addressing the architecture of the internal local server, their components, and their interaction. This chapter aimed at filling this gap. It presented a comprehensive smart building system, including the software architecture. The performances of this system were investigated through monitoring fifteen social housing apartments for one year.

1.2 Smart Building Architecture:

The architecture of the smart building is based on five layers as shown on figure 1.1. All the layers are connected to each other in order to change data and queries. The fives layers are:

- Layer 1 - Physical layer: It is the lowest layer of the smart building architecture which stands for the Instrumented building.
- Layer 2 - Sensors & Actuators Layer: It is composed of:

    - Wireless sensors that sense different indoor parameters such as temperature, humidity…etc and send it through the network to the local server (Data Management Layer).
    - Actuators that perform Actions such control of the lights based on the local server queries.
- Layer 3 - Data Transmission Layer: it includes the network and a set of protocols that operate the communication between the sensors, the actuators and the local server as well as the communication between the local server and the cloud.
- Layer 4 - Data Management Layer: It constitutes the central element of the smart building system. It consists of the local server which is responsible for storing, cleaning and analyzing the data sent by sensors. In addition to controlling the actuators.
- Layer 5 - Services Layer: it designates services to occupants such as consumption information, indoor comfort information and building's equipment control.

We distinguish two type of data flow:

- the Monitoring data: allows to monitor the indoor parameters (comfort, consumption, security) of the buildings (Physical Layer) with the help of sensors (Sensors/Actuators Layer) that send the data via the network (Data Transmission Layer) to the local server (Data management Layer) in order to analyze and store them. A Users interface hosted on the local server allows the end-users (Services Layer) to consult the data of their buildings and the graphs of their consumptions in real time. The service layer is composed of the user interface and the end users (occupants and managers).

- The Control data: allows the end-users to control the different elements of the building such as lights, water consumption, etc. via the user interface, which communicates the command to the local server. The local server identifies the correct actuator identifier, then it broadcasts the command with the actuator identifier in the network, the actuator (Sensors/Actuators Layer) with the same identifier perform the action.

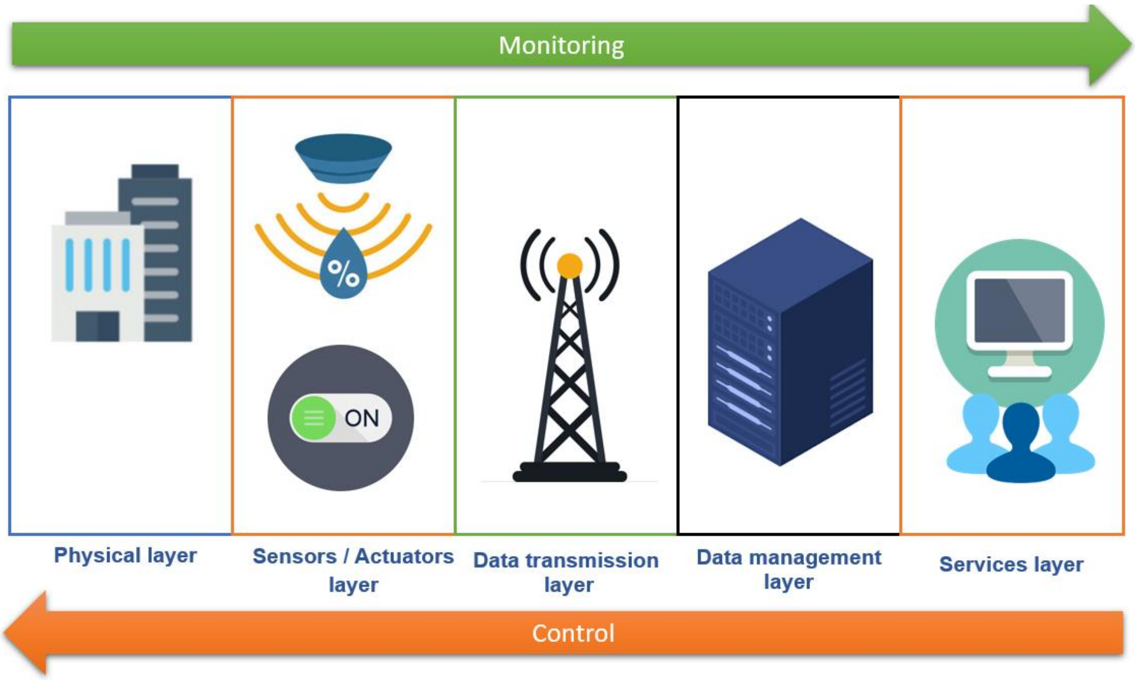

Figure 1.1 Architecture of the smart building system

1.3 Layer 1- Physical layer (buildings):

The physical layer is the first layer of the smart building system. It consists of the buildings and its infrastructure. Figure 1.2 shows an instrumented building plan. It provides an environment to study the internal comfort parameters of different pieces of the building and to monitor the consumption of the occupants. In addition to the possibility of controlling the equipment such as lights.

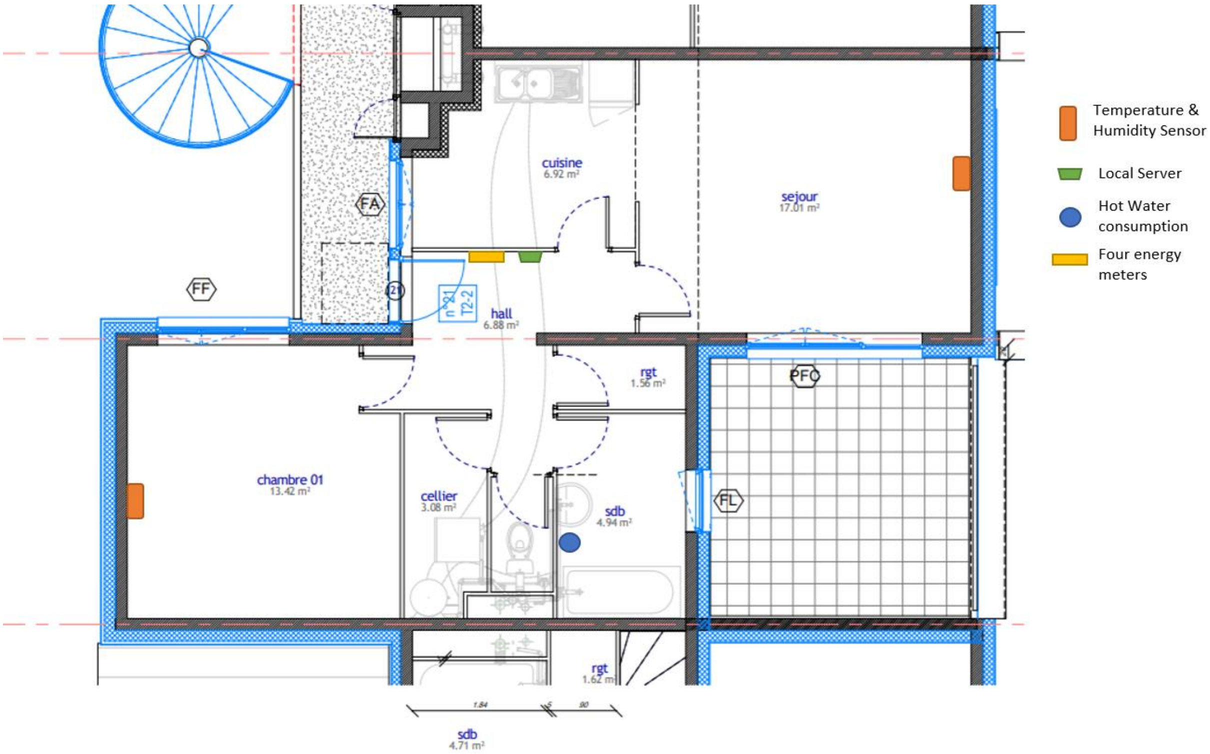

Figure 1.2 Instrumented Building

1.4 Layer 2 - Sensors & actuators Layer

The sensor & actuators Layer aims to gather data from the environment through wireless sensors and control the building's equipment using actuators. Figure 1.3 shows the architecture of this layer. The wireless sensor consists of the sensor unit which is responsible for capturing the physical quantity and transform it into a digital value, to be processed and stored by the processing and memory unit. When the data is ready, the communication unit sends the data the local server and waits for requests that might be sent by user to change the parameters of the sensor such as the transmission frequency. The wireless actuator consists of control units that execute the queries coming from the processing to control the building equipment.

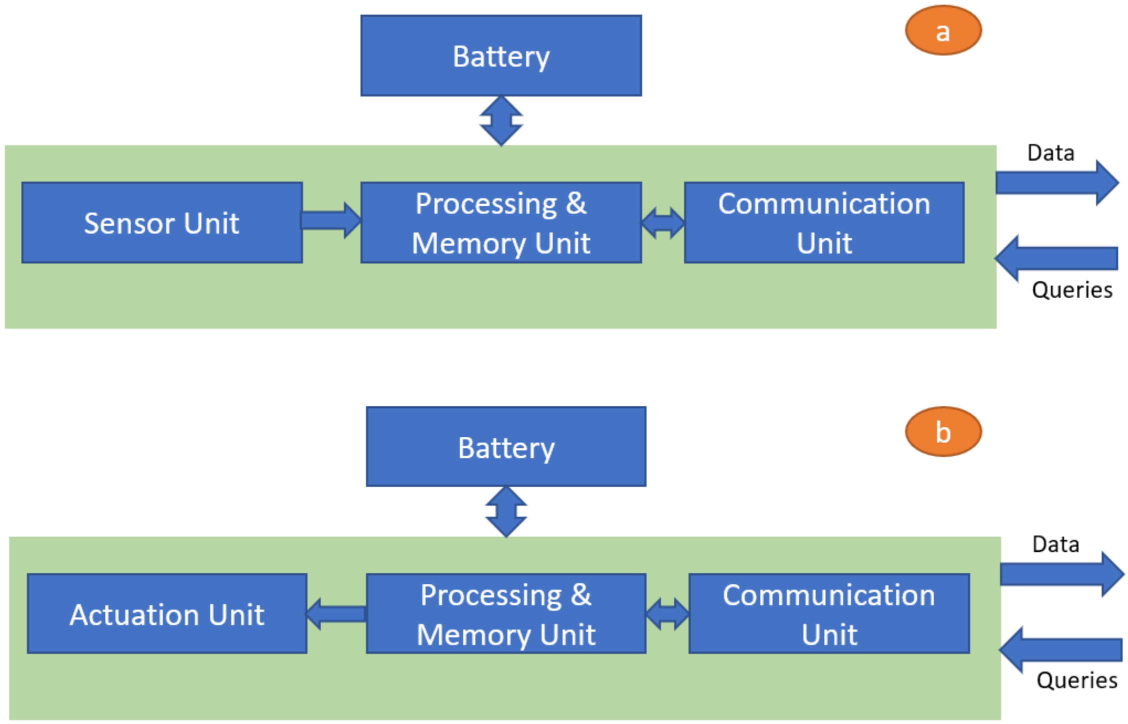

Figure 1.3 Architecture of a) a wireless sensor b) a wireless actuator

1.4.1 Sensors

1.4.1.1 Comfort sensors

Comfort sensors are used to quantify occupant comfort and indoor air quality. They allow to investigate the comfort parameters and their correlation with the other. The system includes the following sensors:

- THLN sensor (figure 1.4): This sensor was developed in our laboratory. It contains four sensors: temperature, humidity, lighting and noise sensor. It is based on Panstamp NRG module and uses SWAP protocol to send and receive data from the gateway.
- NODON temperature and humidity sensor [1]: It allows to monitor both temperature and humidity. It uses Photovoltaic energy.

[1] https://nodon.fr/nodon/capteur-temperature-humidite-enocean (Accessed on 16 June 2021).

- E4000[2]: it is an air quality sensor which contains four sensors, temperature, humidity, CO2 and VOC. It uses the Enocean protocol.
- Eltako multifunction probe FCO2TF65-WG[3]: is another alternative that we used to measure the CO2 concentration, temperature and humidity.

Figure 1.4 THLN sensor

Table 1.1 summarizes the technical specifications of the comfort sensors such as the range and, precision and communication protocol.

Table 1.1 Technical specifications of the comfort sensors.

[2] http://nano-sense.com/wp-content/uploads/2018/08/E4000-Fiche-produit-detaillee.pdf Accessed on 16 June 2021).

[3] https://www.eltako.com/fileadmin/downloads/fr/Fiches_techniques/Fiche_technique_Eltako-radio_FCO2TF65.pdf (Accessed on 16 June 2021).

Name	Sensor	Range	Precision	Protocol
THLN Sensor	Temperature	-10°C to 85°C	± 0,4°C	SWAP
	Humidity	0 to 100%	± 3%	
	Lighting	0 to 500 Lux	±10	
	Noise	20 to 90 dB	±2	
NODON temperature and humidity sensor	Temperature	0°C to 40°C	± 0,16 °C	EnOcean
	Humidity	0 to 100%	± 3%	
E4000 Probe	Temperature	de 0° to + 50°C,	± 0,3°C	EnOcean
	Humidity	10% to 90% RH	± 3%	
	CO2	390 to 3500 ppm	± 100 ppm	
	COV	Max 300ppm	± 0,1ppm	
FCO2TF65-WG	Temperature	0 à 51°C	--	EnOcean
	Humidity	0 to 100 %	--	
	CO2	Max 2550 ppm	--	

1.4.1.2 Consumption sensors

Consumption sensors provide information about occupant consumption. The system includes smart water meter and smart electrical consumption. Two systems were used to measure the electrical consumption:

- Eltako fwz 14-65a[4]: it is energy meter sensor with maximum intensity of 65A and standby loss only 0.5 Watt. It uses enOcean protocol to send data to the gateway.
- Panstamp Water Meter: This is a sensor based on the panstamp NRG2 module. We developed it in our laboratory. It sends a packet to the gateway for each litter consumed using the SWAP protocol.

1.4.1.3 Security sensors

The system includes the following safety and security sensors:

[4] https://www.eltako.com/fileadmin/downloads/fr/Fiches_techniques/Fiche_technique_Eltako-radio_FWZ14-65A.pdf (Accessed on 16 June 2021).

- NODON SDO2105[5]: Door and window opening detector, it sends a packet to the gateway every time a person opens or closes a door or a window using the enocean protocol.
- GIGACONCEPT DO13-421B-E[6]: Wall presence sensor, it sends a packet to the gateway using the enocean protocol each time it detects a movement of a person or an object.
- Eltako FRW-WS[7]: it is an enocean wireless smoke detector that sends a packet to the gateway when it detects smoke in addition to a loud beep.

1.4.2 Actuators

The following actuators are used to control the building equipment:

- Wireless valve actuator[8]: is a wireless actuator that is used to adjust the flow rates to radiators in hot water and steam heating systems. It communicates wirelessly with the local server using enocean protocol.
- Wireless actuator light controller FLC61NP-230V [9]: an enocean wireless light controller with 5 selectable operating modes
- Dual-channel wireless switch actuator [10]: is an enocean dual-channel wireless switch. Every channel controls a group of 220V electronic lighting loads.

[5] https://nodon.fr/nodon/detecteur-douverture-portes-et-fenetres-enocean (Accessed on 16 June 2021).
[6] https://market.thingpark.com/media//datasheet//d/o/do13-421b-e.pdf (Accessed on 16 June 2021).
[7] https://www.eltako.com/fileadmin/downloads/fr/_bedienung/FRW-ws_30000053-2_frz.pdf (Accessed on 16 June 2021).
[8] https://www.enocean-alliance.org/fr/product/illumra_wireless-valve-actuator/ (Accessed on 16 June 2021).
[9] https://www.enocean-alliance.org/fr/product/eltako_flc61-np/ (Accessed on 16 June 2021).
[10] https://www.enocean-alliance.org/it/product/dual-channel-wireless-switch-actuator/ (Accessed on 16 June 2021).

1.5 Layer 3 - Data Transmission Layer

The data transmission layer ensures connection between the sensors & actuators and the local server as well as the connection between the cloud and the local server. Data transmission is based on short-range protocols and long range:

1.5.1 Short Range Protocols

Short range Protocols are used for the communication between the sensors/actuators and local server using low-power consumption and low-cost solutions. The following protocols are used:

- **NFC (Near-field communication)**: is a standard for contactless radio frequency communication at very short distances (few centimeters), allowing simple communication between two electronic devices (tag and the reader). Each NFC tag has a unique identifier and can contain small amount of data.
- **BLE**: also known as Bluetooth Smart, is a short-range communication technology using short wavelength radio waves with a minimal amount of energy. It is designed to enable data collection from sensors that generate data at a very low rate.
- **Z-wave**: is a low power wireless protocol designed for battery or electrically powered devices and widely used for Smart buildings as well as small-size commercial domains.
- **Wifi**: It is the most used standard for Wireless Local area network (WLAN).it comes with a new standard IEEE 802.11ah that provide more scalability, QoS and energy efficiency.
- **Zigbee**: is a short-range technology provide a low-power consumption, low complexity and low-cost advantages. It uses IEEE802.15.4 standard as its physical layer.

- **Enocean**: is a short range, low complexity and secure protocol used by battery less and wireless sensors.
- **SWAP**: a lightweight, open-source and low consumption protocol. Used for short range communication.

1.5.2 Long Range Protocols

Long range protocols are used for communication between local server and cloud or remote sensors. They include:

- **LTE**: is long range protocol based on GSM/UMTS network. It covers fast travelling devices and provide broadcasting and multicasting services. It used for high-speed data transfer between mobiles.
- **NB-IoT (Narrow Band Internet of Things)**: is wide-area cellular connectivity for the Internet of Things provide a low-cost, low power solution.
- **Lora/LoraWane:** is a long-range wireless protocol, it used in long-lived battery-powered devices, where the energy consumption is of paramount importance. It operates on many ISM bands depending on the region in which it is deployed such as 433MHz, 868MHz or 915MHz ISM bands.
- **Sigfox**: is a French telecommunications operator of the Internet of Internet. Sigfox operates in the 868- MHz frequency band. The end-device (Sensors) can send up to 140 messages per day, with a payload size of 12 octets.

The proposed system is based on SWAP and Enocean protocol, which use energy harvesting such as Piezoelectric and Photovoltaic. The long-range communication is based on the Sigfox network, which is dedicated to IoT. It uses micro-messages (size: 12 bytes) at 10 minutes time interval.

1.6 Layer 4: Data Management Layer

Data management layer is the core layer of the smart building architecture and the gateway between the sensor/ actuator layer and the services layer. It consists of the local server which perform the following tasks:

- Receive and store the data sent by the sensors
- Send commands to the actuators
- Organization of the data in a semantic structure of the building.
- Detect sensor errors.
- Data visualization.
- Communication with the central server.

1.6.1 Hardware Specifications

Our Local server is based on Raspberry pi 3 board which is a powerful low-cost ARM based processor board as shown in Table 1.2. It performs functions like any computer with the advantage that it has a reduced physical structure (Dutta et al. 2017). It is equipped with Enocean and Panstamp modules to send commands to actuators and receive data from sensors. It is also connected to the Arduino MKR FOX 1200 board via USB as shown in figure 1.5 to communicate with Sigfox network. The Panstamp module contains an integrated DS1338 chip which is used as a real time clock module for the gateway.

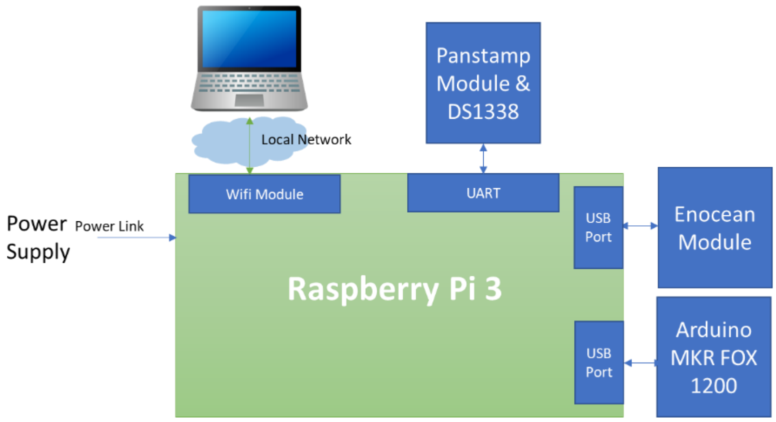

Figure 1.5 Block-diagram of the gateway

Table 1.2 Raspberry Pi 3 technical specifications

CPU	4× ARM Cortex-A53, 1.2GHz
GPU	Broadcom VideoCore IV
SoC	Broadcom BCM2837
RAM	1GB LPDDR2 (900 MHz)
Storage	microSD (16Go in our case)
Networking	10/100 Ethernet, 2.4GHz 802.11n wireless
Bluetooth	Bluetooth 4.1 Classic, Bluetooth Low Energy
GPIO	40-pin header
Ports	HDMI, 3.5mm analogue audio-video jack, 4× USB 2.0, Ethernet, Camera Serial Interface (CSI), Display Serial Interface (DSI)

1.6.2 Software Architecture

This section presents the software architecture implemented in the local server. It includes two parts as shown in figure 1.6: the database and the software backend architecture.

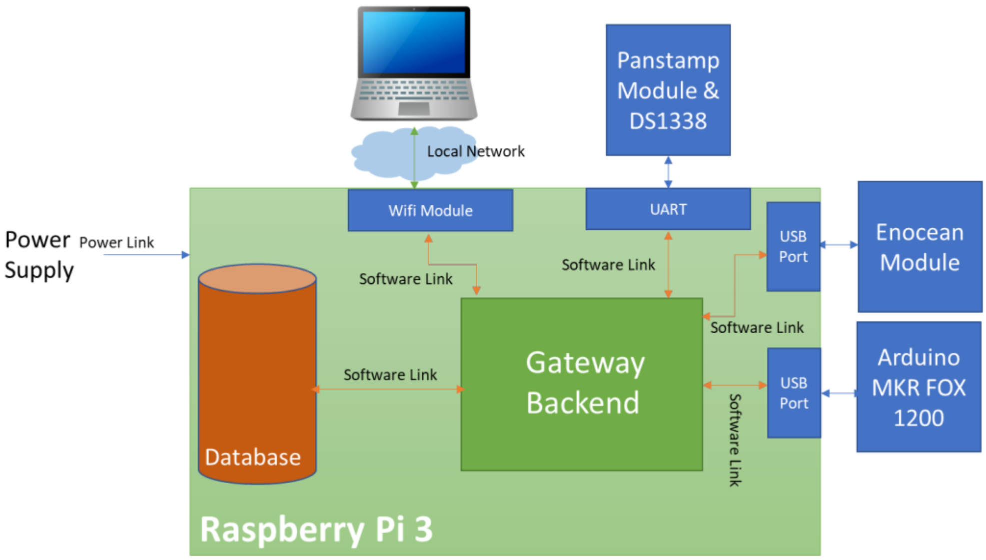

Figure 1.6 Block-diagram of the gateway

1.6.2.1 Database:

The database is the main component, which aims to store and retrieve the data collected from sensors. The major types of the databases are:

- Relational database: is a set of data elements with predefined relationships between them. These items are organized into a set of tables consisting of columns and rows. Tables are used to store information about the objects that should be represented in the database.
- NoSQL database: is an approach to database design that can adapt a wide variety of data models, including formats with keys, documents, columns, and charts. It is particularly useful for working with large distributed datasets.

The system is based on the relational database, which contains several data tables. These tables are connected via a special key to organize the data in a semantic structure as shown in figure 1.7. This organization allows the installation of our in any building because of its flexibility. We used annotation adapter which means sensor module, for example THLN sensor is an adapter containing four different sensors. Each adapter and sensor have its own type. Then, we defined their relationship using table 'adapter_sensor_types'. This method allows us to add any sensor or module to our system. When we add a new adapter to our database, the system will automatically create a data table for each sensor of the adapter. This architecture avoids storing all the collected data in one table, which could alter the system performance.

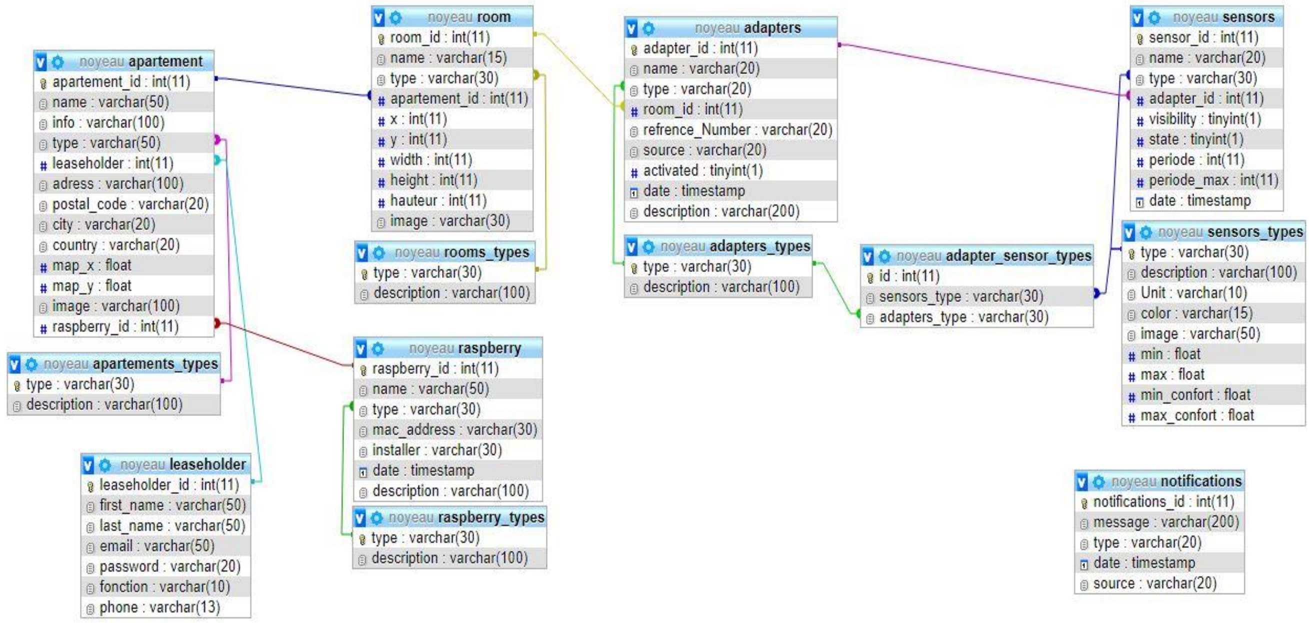

Figure 1.7 Database structure

1.6.2.2 Software Architecture

The backend of the local server is based on the open-source server environment nodejs, which uses javascript. Nodejs[11] was selected for f its high performance, scalability and asynchronous and event-driven programming. The software architecture consists of 9 modules as shown in figure 1.8. Each module has a specific role as described below.

[11] https://nodejs.org/en/ (Accessed on 16 June 2021).

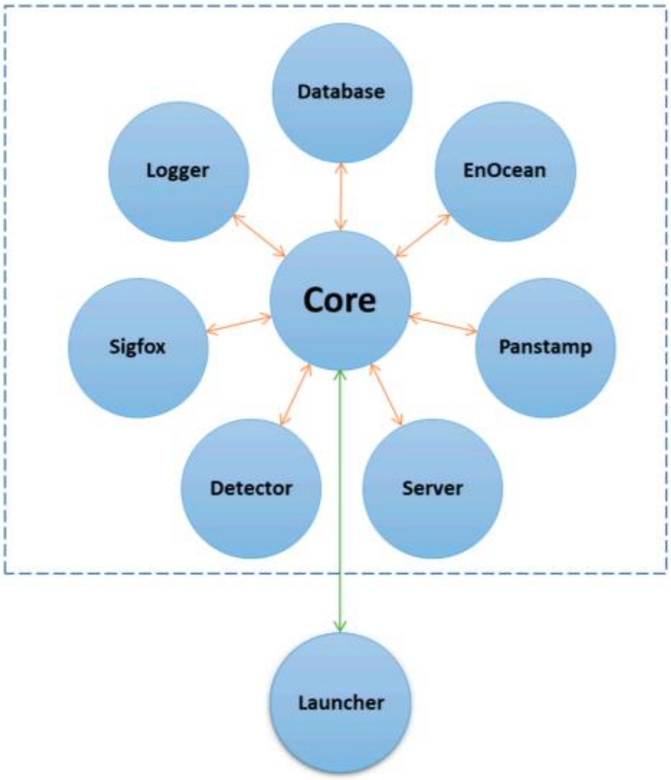

Figure 1.8 Software modules

a) Core:

The core is the heart of the local server and the maestro that guarantees the communication between the different modules. It also operates the system commands such as restarting, shutting down and modifying the WIFI parameters of the raspberry Pi. Figure 1.9 shows the flowchart of the core.

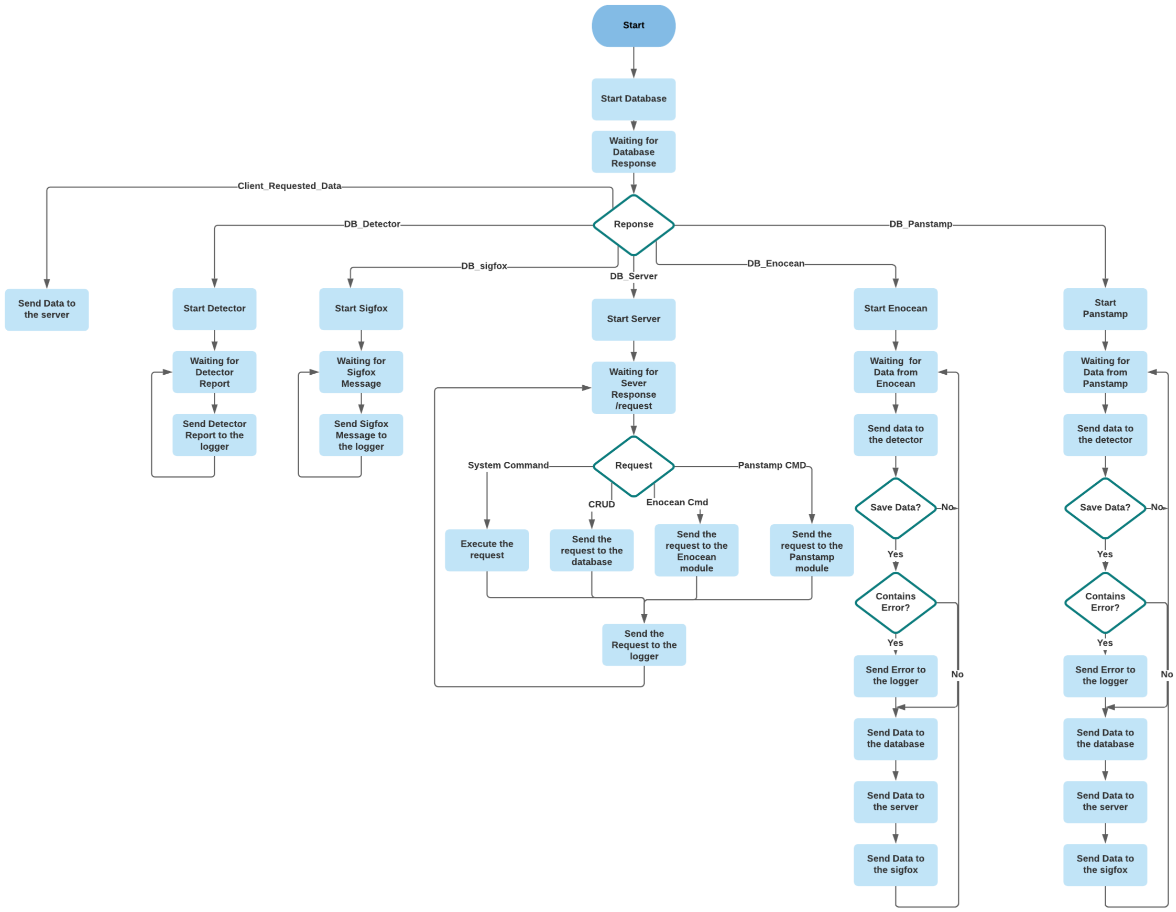

Figure 1.9 The flowchart of the core module

b) Launcher:

The launcher is an import module in the software architecture that keeps the core alive whenever it stops as shown in figure 1.10, it is based on forever-monitor library[12].

[12] https://www.npmjs.com/package/forever-monitor (Accessed on 16 June 2021).

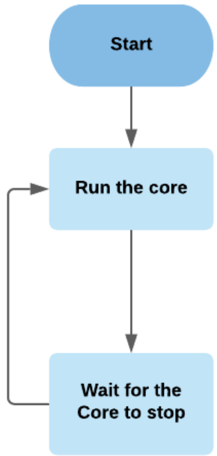

Figure 1.10 The flowchart of the launcher module

c) Enocean

This module communicates with Enocean sensors to receive data and send commands in addition to encryption and decryption of packets. Figure 1.11 describes the mechanism of this module.

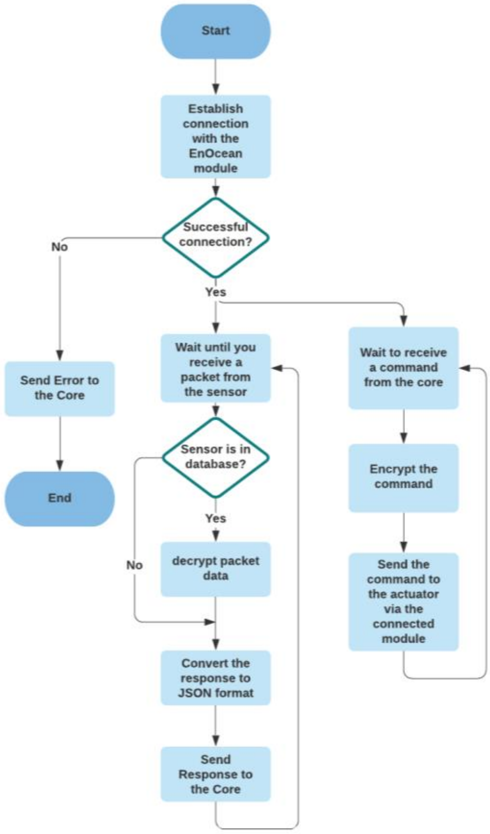

Figure 1.11 The flowchart of the Enocean module

d) Panstamp

This module communicates with Panstamp sensors to receive data, send commands encrypt and decrypt the packets. This module works as Enocean module.

e) Detector

The detector detects values errors and malfunctions of the sensors by defining the functional rules such as the measuring range of the sensors in addition it has a sensor period check function which aims to set a virtual sensor period, for example if we have a sensor that sends data every five minutes but we want to store data every 15 minutes, we will define a virtual period of 15 minutes for the detector to reject all data sent in less than 15 minutes. The flowchart of this module is shown in figure 1.12.

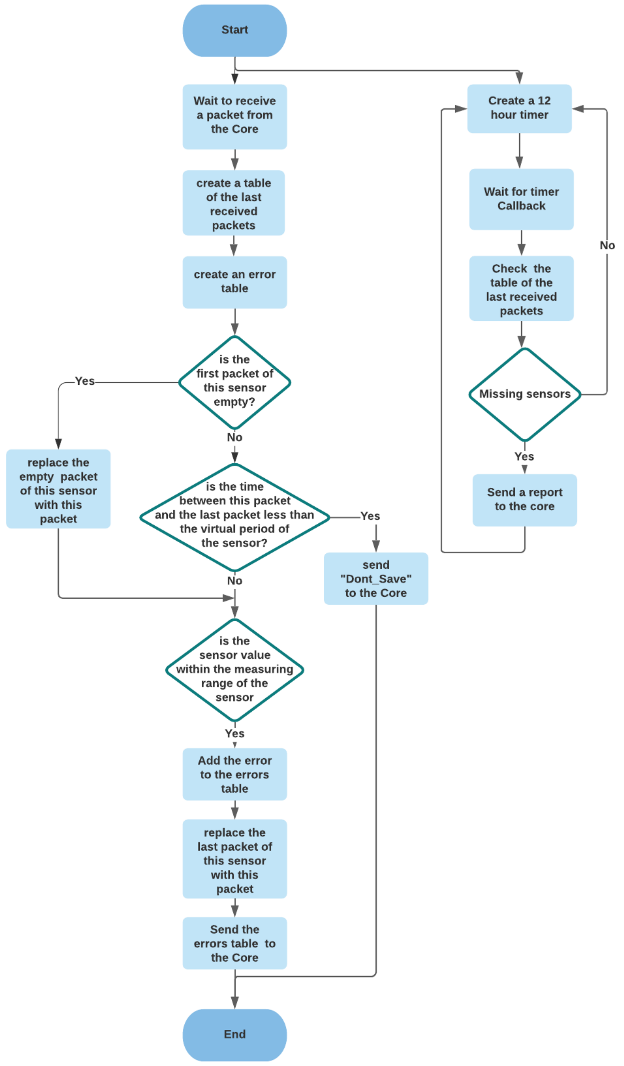

Figure 1.12 The flowchart of the detection module

f) Logger

The logger records the important operations operated by the system as well as the errors sent by the core as show in figure 1.13.

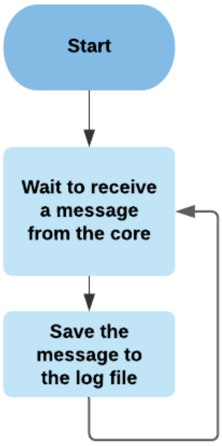

Figure 1.13 The flowchart of the logger module

g) Webserver

The web server provides a webpage interface (figure 1.14) that connects users to the system. It is built with express library[13]. The web page is developed using html, css and javascript. The latter is used to perform calculations in the browser to reduce pressure on the raspberry. In addition, it receives real-time data from the server using the socket-io library[14]. Figure 1.15 shows the flowchart of the server.

[13] https://www.npmjs.com/package/express. (Accessed on 16 June 2021).
[14] https://socket.io/. (Accessed on 16 June 2021).

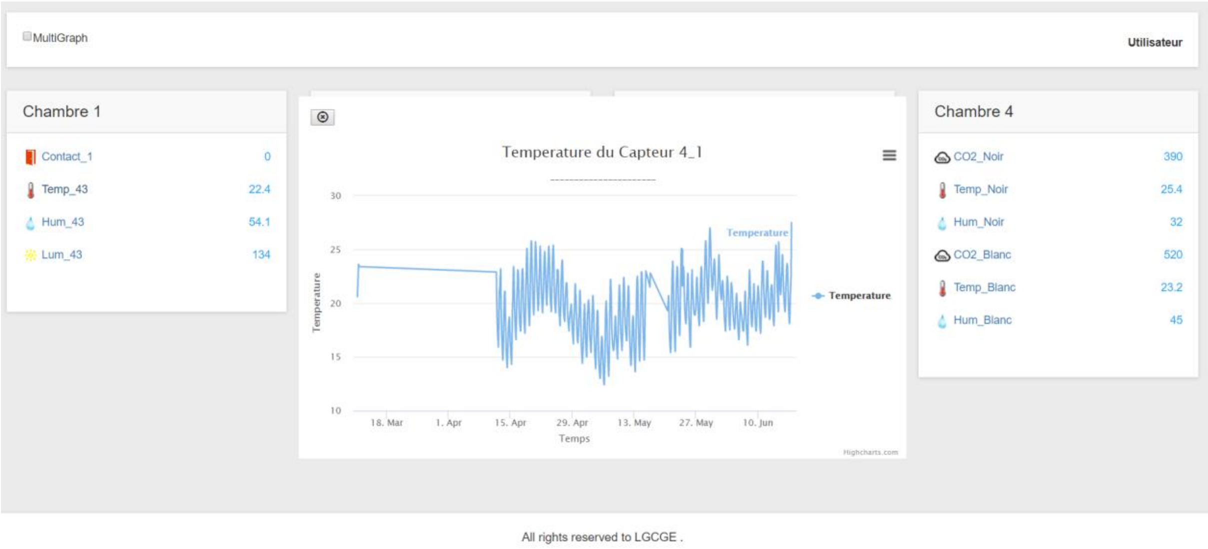

Figure 1.14 User's interface

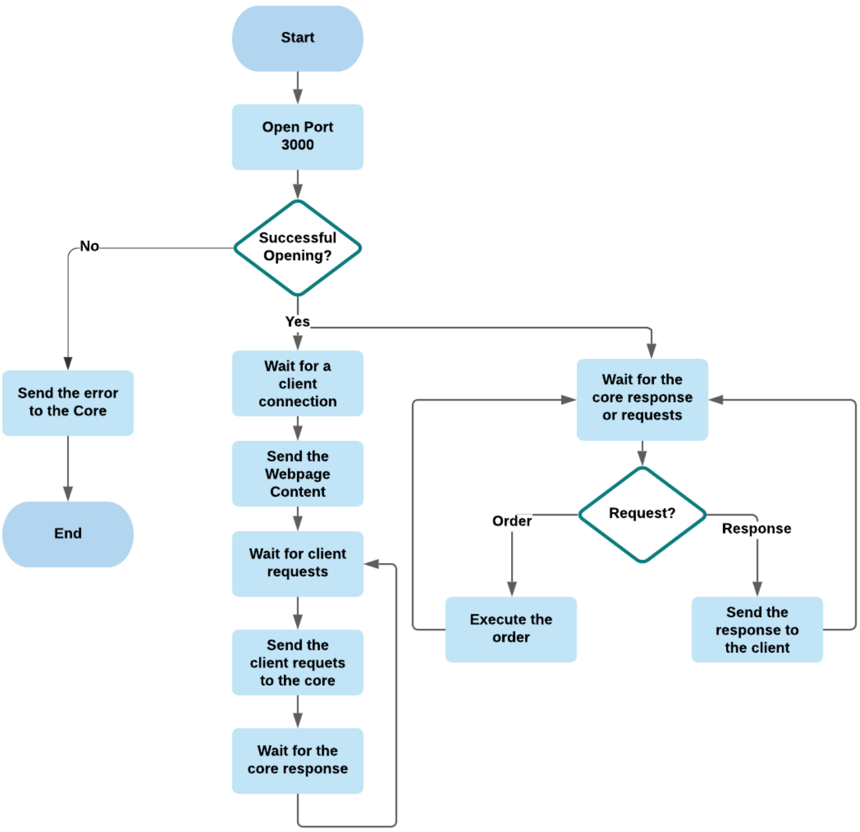

Figure 1.15 The flowchart of the web server

h) Database

It is an important module, which manages the database (storage and retrieval of data) and creates different copies of the data intended for the other modules to reduce the number of operations with the database which makes the system faster. Figure 1.16 shows the flowchart of the database module.

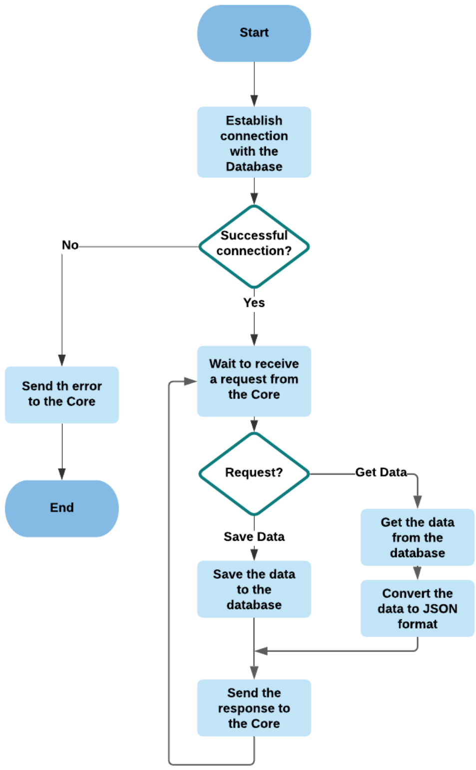

Figure 1.16 The flowchart of database module

i) Sigfox

Sigfox module is responsible for communication with Arduino MKR FOX 1200 to send packets to the cloud. Figure 1.17 shows the flowchart of the Sigfox module.

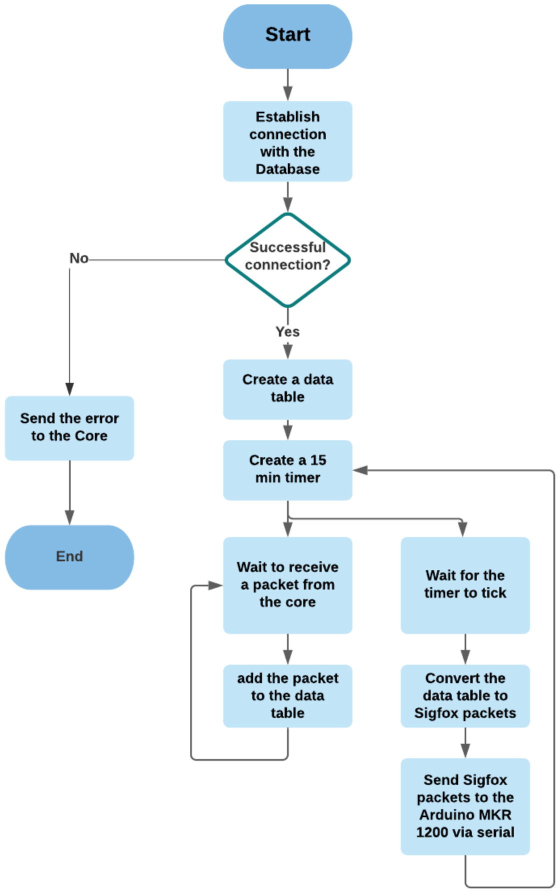

Figure 1.17 The flowchart of the Sigfox module

1.6.3 Interactions between software modules

During tests, the software architecture showed flexibility, speed, ability to detect sensor errors, and executes tasks because of the asynchronous processing of nodejs. Figure 1.18 shows the gateway software and hardware components and their links. The following scenarios were created to break down the interactions of software modules:

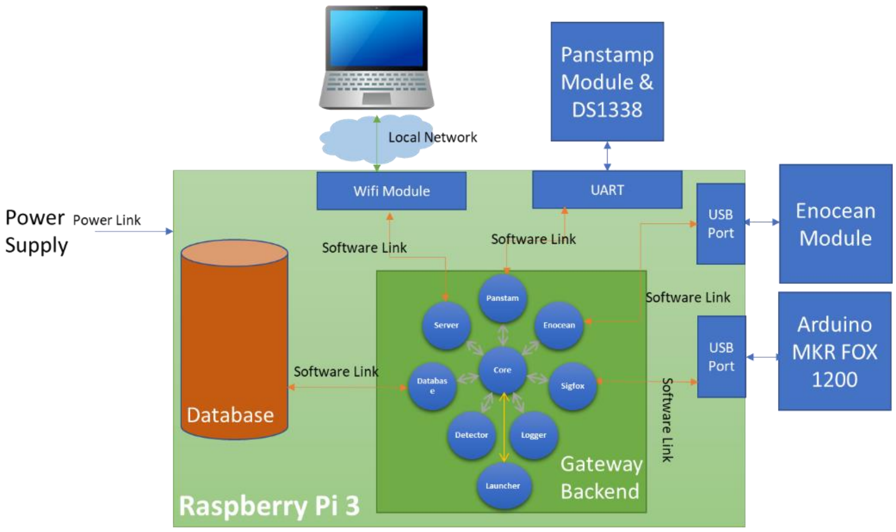

Figure 1.18 Block-diagram of the gateway

a) System Startup:

After powering the raspberry pi, the system will automatically run the launcher code that starts the system core, which starts the database module. The database module creates a custom copy of the database for each module in order to make the system faster and reduce the number of operations with the database and send it back to the core to be distributed to other modules as shown in figure 1.19.

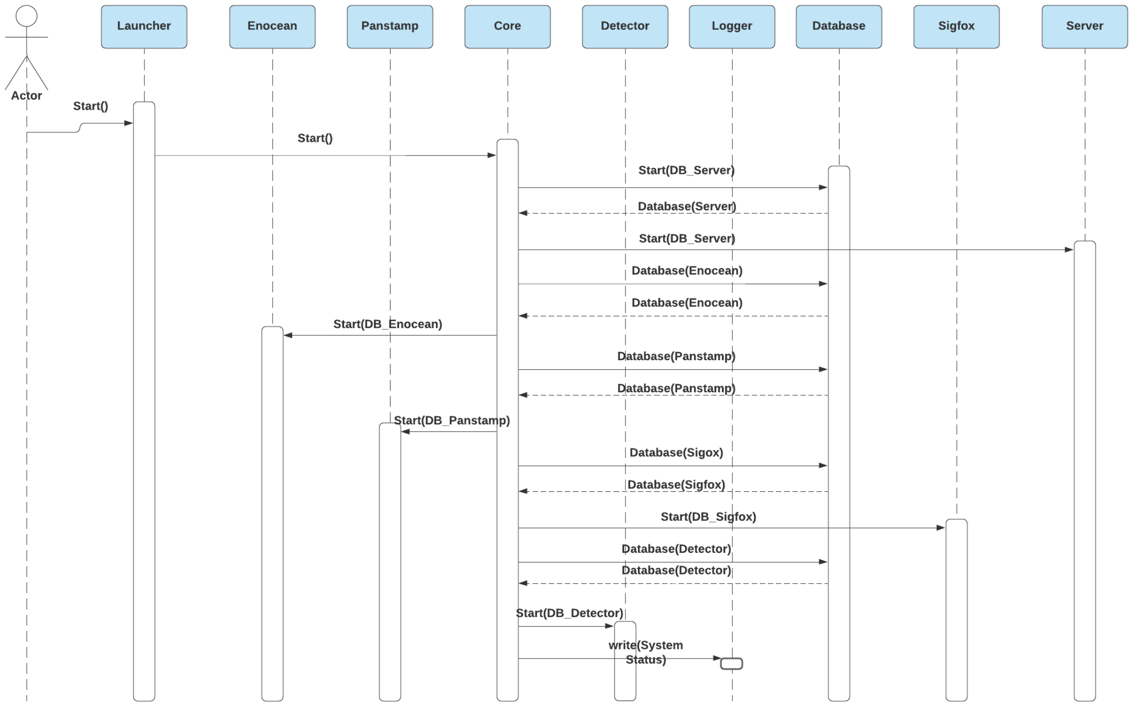

Figure 1.19 The system startup sequence diagram

b) Receipt of sensor the packet:

after receiving the sensor packet via the serial port, the corresponding module checks the existence of the copy of the database. If the copy exists, it sends it directly to the core to be analyzed by the sensor, stored by the database and sent to the server and sigfox module. Otherwise, the packet is sent directly to the core to be added to the log file by the logger module. Figure 1.20 shows the sequence diagram for receiving a sensor packet.

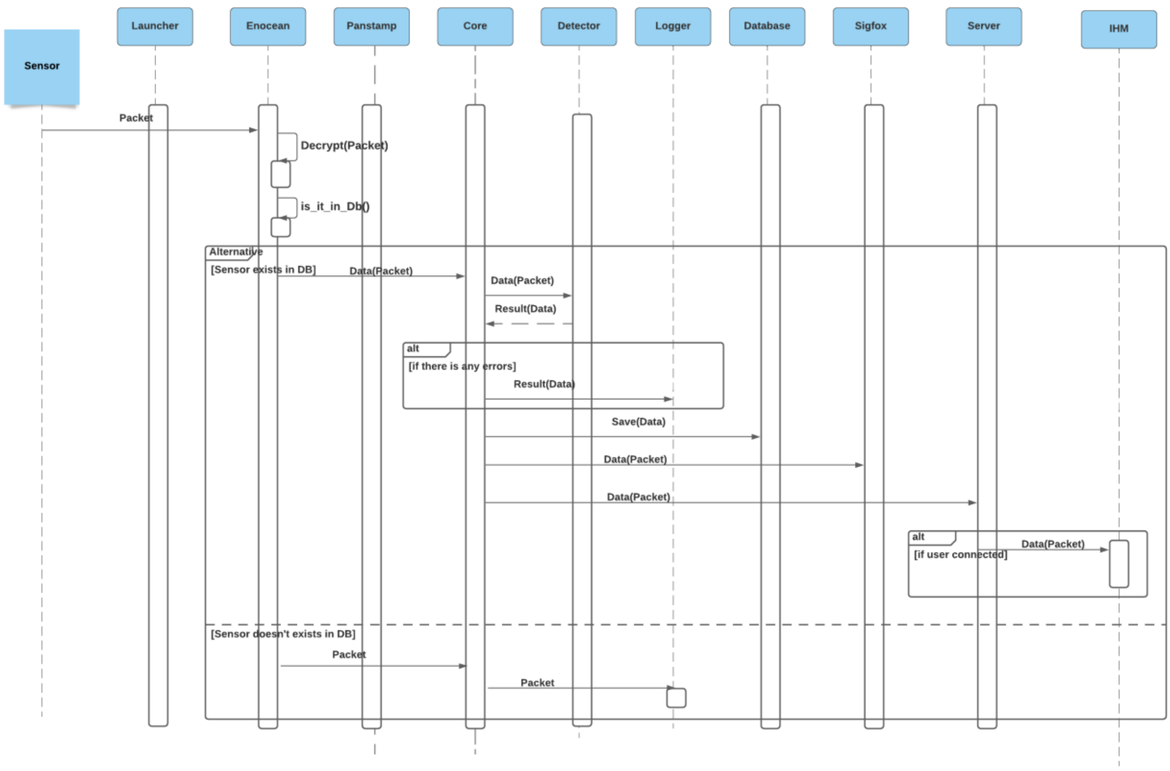

Figure 1.20 Receipt of sensor the packet sequence diagram

c) Receipt of occupant's request

The system has a web page interface that allows occupants to make requests such as adding sensors, controlling actuators, viewing sensor history, download data ... etc. The occupant’s request goes directly to the server module, which sends it to the core to be executed by different modules if necessary and return the response back via the server module as shown in figure 1.21.

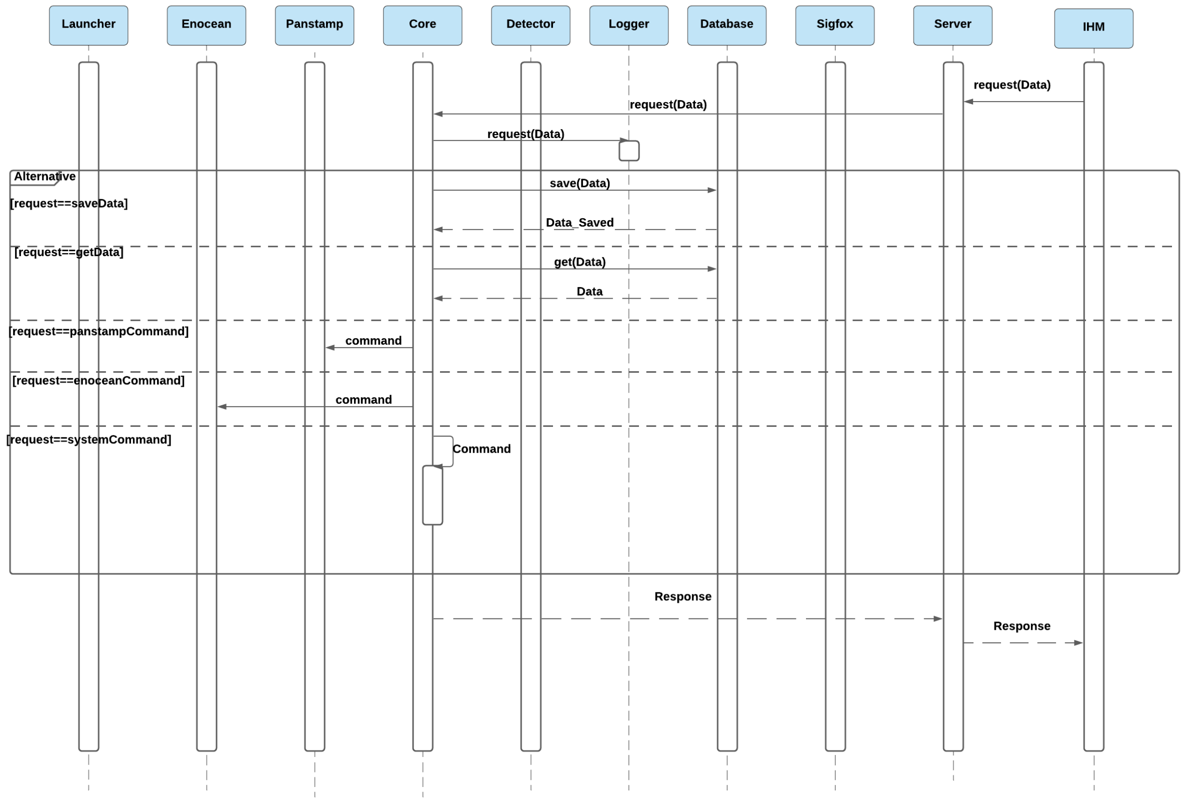

Figure 1.21 Receipt of occupant's request sequence diagram

1.7 Layer 5: Services Layer:

The services layer is the top layer of the smart building architecture. It provides services to t users (occupants and managers). It is responsible for data visualization such as the historical and the real time data of sensors and controlling the building's equipment. In addition, it manages the interaction between users and the local server. We distinguish two types of users:

- Occupants: They have the right to access real-time and historical data using a graphic interface. They have the possibility to control the building's equipment through the interface (Figure 1.22).
- Managers: They have more privileges and control over the interface (Figure 1.23) such as:

- Add, remove or change sensors/actuators.
- Add, remove or change rooms.
- Activate / deactivate sensors.
- Export the data to a CSV file.
- Restart/ Shutdown the system.
- Change sending period of sensors.
- Check system logs and sensor status.

Figure 1.22 The occupant interface.

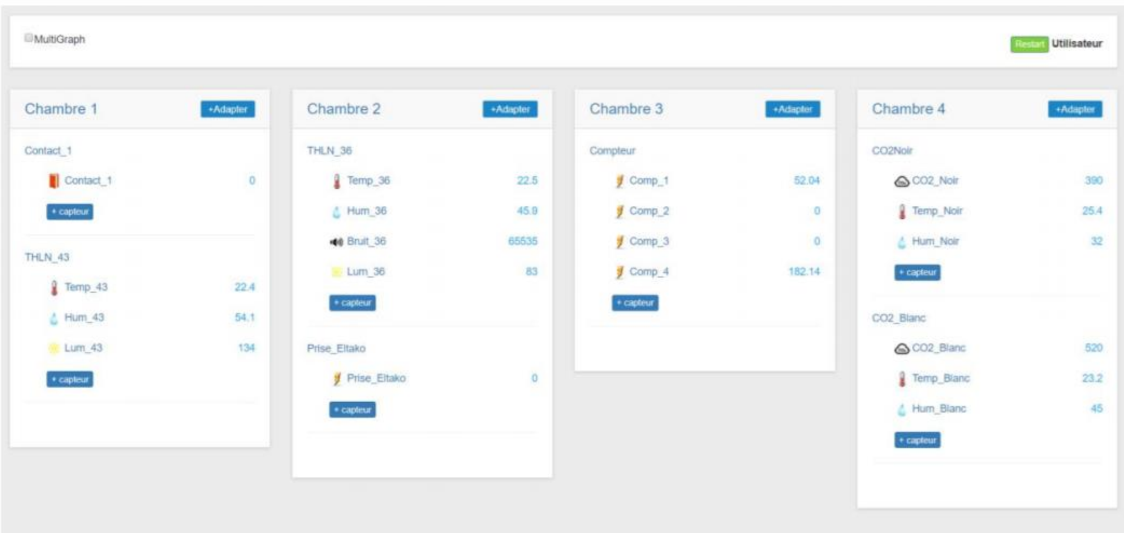

Figure 1.23 The manager's interface

1.8 Conclusion:

This chapter presented the methodology followed for the design and construction of a smart building system, that allows both buildings' monitoring and control. This system is characterized by its simplicity, reliability, low cost and ease of construction and installation. The system could be extended easily to host new components and services.

The system allows a large set of smart services, such as monitoring of indoor comfort, air quality, fluid consumption and building safety. It allows also automatic or on-line control of the building equipment and appliance. The system offers a friendly environment to users with a graphic interface.

The hardware and software components were selected or developed to ensure high performances in terms of low energy consumption, rapid data collection and treatment.

The chapter includes a detailed description of the hardware and software components as well as the specifications of the materials and the technologies. Provided information could be used by academics and professionals to develop smart building system.

In the next chapter, we will present the analysis of the impact of the indoor classroom environment on the effectiveness of student learning, which is based on smart classroom monitoring and a questionnaire on students' evaluation of comfort conditions and learning effectiveness.

2 Chapter 2: Use of smart monitoring and users' feedback for to investigate the impact of the indoor environment on learning efficiency

This chapter was submitted to the International Journal Environmental Economics and Policy Studies (Springer). The paper is in the revision process.

Journal Link: https://www.springer.com/journal/10018

2.1 Introduction

This chapter presents an investigation of the indoor comfort of classrooms and its impact on students' learning efficiency. Several approaches have already been used to investigate the quality of the indoor classroom environment and its impact on students' learning capacity. According to Ricciardi and Buratti (2018), students' activity and productivity in classrooms require a good indoor environment, including thermal, acoustic, and visual comfort. Cui et al. (2013) Ricciardi and Buratti (2018) showed that good indoor air quality has an important impact on concentration, absenteeism, and the apparition of disturbance symptoms. Bajc et al. (2019) used a set of sensors in classrooms at the University of Belgrade to monitor the temperature, relative humidity, CO2, air velocity, and radiant temperature.

The poor indoor comfort conditions could be attributed to different factors such as low energy efficiency of buildings, lack of ventilation, and occupants' capacity to afford energy expenses. Consequently, energy-saving constitutes an efficient solution for the improvement of indoor comfort conditions. In a recent paper, Belaïd and Joumni (2020) highlighted the significant role of occupants' behavioral towards energy saving. They suggested intervention strategies to encourage energy-saving behaviors such as information, education, incentives measurements, and enablement. Belaïda et al. (2019) argued that improving energy efficiency requires regulation reforms, data collection, technical capacity improvement, and institutional reforms.

Analysis of the relationship between indoor comfort conditions and students' loss of productivity showed that indoor thermal comfort significantly impacts students' learning efficiency. Zhong et al. (2019) investigated the indoor comfort conditions in four classrooms in an institutional building in Canada. Monitoring concerned CO2 concentration, sound level, temperature, relative humidity, barometric pressure, illuminance, and airspeed. As a result, they found that the location of the building, classroom conditions, and the operations of the HVAC system have a significant impact on the indoor environmental quality.

Bluyssen et al. (2018) surveyed 1311 schoolchildren in 21 schools in the Netherlands to investigate the relationship between classroom characteristics and the health and comfort of children. The survey included data collection about the buildings and classrooms and a schoolchildren questionnaire emphasizing age, gender, location in the classroom, feeling, health, and home environment. Results showed that 87% of the schoolchildren were bothered by noise, 63% by smells, and 42% by sunlight. A third of the schoolchildren reported discomfort related to temperature, whereas 26% suffered from allergies. About 16% of the children had fever, eczema, or rhinitis. Ricciardi and Buratti (2018) used a questionnaire and a monitoring system to investigate the students' perception of thermal, acoustic, and visual comfort in classrooms. The study showed a high correlation between the background noise and the students' perception of prolonged noises. Yildiz et al. (2019) investigated the students' feelings under different classroom indoor environments. The investigation included a collection of 1782 students' responses as well as monitoring the classrooms' temperature, relative humidity, radiant temperature, airspeed, and CO2 concentration. Results showed that only 55% of the students were satisfied with the thermal comfort. Recently, Pistore et al. (2020) conducted a non-invasive survey to investigate the satisfaction of secondary school students in classrooms. They used a questionnaire to collect data about students' profiles and satisfaction with thermal, visual, acoustic, and air quality conditions. Results showed that 62% of students complained of thermal discomfort, and 53% changed clothing levels to achieve thermal comfort. Around 64% of students complained of unpleasant odor quality.

In most of the previous studies, authors did not consider the spatial and temporal variation of the comfort conditions in the classroom. The classroom was regarded as a homogeneous space. Since the comfort parameters could have significant spatial and temporal change (Tariku and Ying Simpson (2014) and Curi et al. (2017)), this change should be considered in the analysis. In addition, previous studies focused on the impact of indoor conditions on occupants' comfort. The impact of the indoor conditions on students' learning capacity was not investigated. The contribution of this paper to the scientific literature is twofold. The first contribution concerns investigating the spatial and temporal variations of the indoor comfort conditions using multi-sensors devices on students' desks and the students' feedback. The second contribution discusses the impact of the indoor comfort conditions on students' capacity learning. This investigation was conducted using comfort sensors data and students' feedback. The chapter presents the methodology of this research, including data collection and data analysis focusing on the spatial and temporal variations of the comfort conditions and their impact on students' learning efficiency.

2.2 Methodology and materials

2.2.1 Methodology

This research is based on data collected in classrooms at the engineering school Polytech'Lille in the North of France. Data were collected using smart multi-sensor devices, which measure the indoor temperature, humidity, and CO2. A questionnaire was used to collect students' assessment of comfort conditions and learning efficiency. The learning efficiency was presented to students as a measurement of their capacity to follow and participate in the teaching activity. The assessment score ranged between 1 (very low) to 5 (excellent). Collected data were then analyzed with the objective to (i) explore the spatial and temporal variation of the indoor comfort parameters, (ii) analyze the students' perception of the indoor comfort conditions and their correlation with recorded physical values, and (iii) analyze the correlation between learning efficiency and the comfort conditions.

2.2.2 Data collection

A set of Netatmo home coach stations was used to monitor the indoor comfort conditions. Stations were located at the students' desks to investigate the spatial variation in the comfort conditions. The station was set up to record the temperature, humidity, and CO2 at 10 minutes time intervals. Table 2.1 summarizes the measuring ranges and precisions of the sensors used in this research. Figure 2.1 illustrates an example of the locations of the Netatmo stations during experimentation. It shows that the monitoring system covers the classroom area concerned by the students' presence.

Table 2.1 Characteristics of sensors used in smart classrooms' monitoring

	Measuring range	Precision

Temperature	0°C to 50°C	± 0,3°C
Humidity	0 to 100%	± 3%
CO2	0 to 5 000 ppm	± 50 ppm (0 to 1 000 ppm) ± 5 % (from 1000 to 5000 ppm)

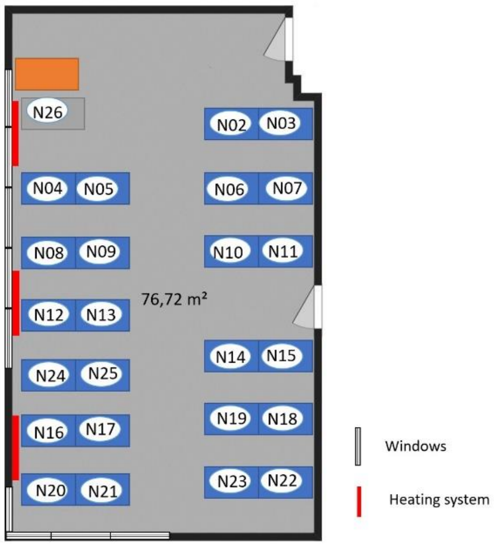

Figure 2.1 Example of localization of the multi-sensors devices in the classroom

Students' assessments of the comfort conditions and learning efficiency were collected using a questionnaire including two parts. The first part concerns the student position in the classroom and the time of the feedback. The second part includes the students' assessment of the comfort parameters according to a score between 1 and 5. A low score denotes low satisfaction. In addition, the questionnaire included the evaluation of the following parameters:

- Temperature comfort
- Humidity comfort
- Learning efficiency

The research program included 5 experiments conducted in three classrooms, which were selected according to the classrooms' floor level and orientation. Table 2.2 summarizes the information about the classrooms. Their capacity varies between 16 and 30 students. They are situated in 2 buildings on the second or third floors. Two rooms are oriented to the North, while only one is oriented to the South.

Table 2.2 Classrooms used in this research (Engineering School Polytech'Lille)

Classroom	Building	Floor level	Orientation	Capacity
1 (A209)	A	2	North	30
2 (A319)	A	3	South	25
3 (B301)	B	3	North	23

Table 2.3 summarizes the conditions of these experimentations, including the day and time intervals of the experiments, the number of students, and the averages of the outside temperature and humidity. Experiments were conducted in December 2019 and January 2020. The outside temperature varied between 3.2 and 10.5° C. The outdoor relative humidity ranged between 75 % and 94%. Two experiments were conducted in the morning, while the others were performed in the afternoon. Three experiments were conducted with closed windows, while in two experiments (2 and 4), windows were opened during the coffee break—the number of students varied between 7 and 21.

Table 2.3 Conditions of conducted experimentations

Experiment	Classroom	Date	Time	Number of Students	Average outside Temperature	Average outside Humidity	Windows status
1	3	16/01/2020	09:00-10:30	18	3.2 °C	100%	Closed during the class
2	2	04/12/2019	09:00-12:30	20	2.85 °C	94%	opened at the coffee break (10:20 - 10:40 am)
3	1	02/12/2019	14:00 - 16:00	13	7.9 °C	78%	Closed during the class
4	1	09/12/2019	16:00-18:00	11	7.05°C	75%	opened at the coffee break (15:30 - 16:00)
5	3	16/01/2020	14:00-16:30	7	10.5°C	86%	Closed during the class

2.2.3 Data analysis

Analysis of recorded data is conducted in two phases. The first phase includes an analysis of the spatial variation of the recorded indoor comfort parameters. The second phase concerns analysis of (i) the students' assessment of the comfort conditions and their correlation with the recorded values and (ii) the impact of the indoor comfort conditions on the learning.

2.3 Results and discussion

The section presents three parts. The first one concerns an analysis of experiment 1, which was conducted with closed windows. The second one discusses experiment 2, which was conducted with closed windows during the class and opened windows during the coffee break. The last part presents the correlation analysis of the results of the five experimentations shown in table 2.3, focusing on the correlation between students' learning efficiency and indoor comfort conditions.

2.3.1 Results of experiment 1

2.3.1.1 Analysis of recorded comfort parameters

Experiment 1 was conducted in classroom 1, January 16, 2020, in the morning. The mean outdoor temperature and relative humidity were 3.2 °C and 100%, respectively. 18 students attended this class. During the class, windows were maintained closed.

Figure 2.2 shows the variation of the indoor comfort parameters. The spatial average value of the temperature increases from 20.3 °C to 25.5 °C. It exceeds the temperature threshold limit value in public buildings in France, which is equal to 19 °C. The average relative humidity increases from 54.0 % to 56.3 %, while the average CO2 concentration varies from 1182 ppm to 4093 ppm. The high level of the initial CO2 concentration is related to a technical delay in starting data recoding. Data recording started around 30 minutes after the class start.

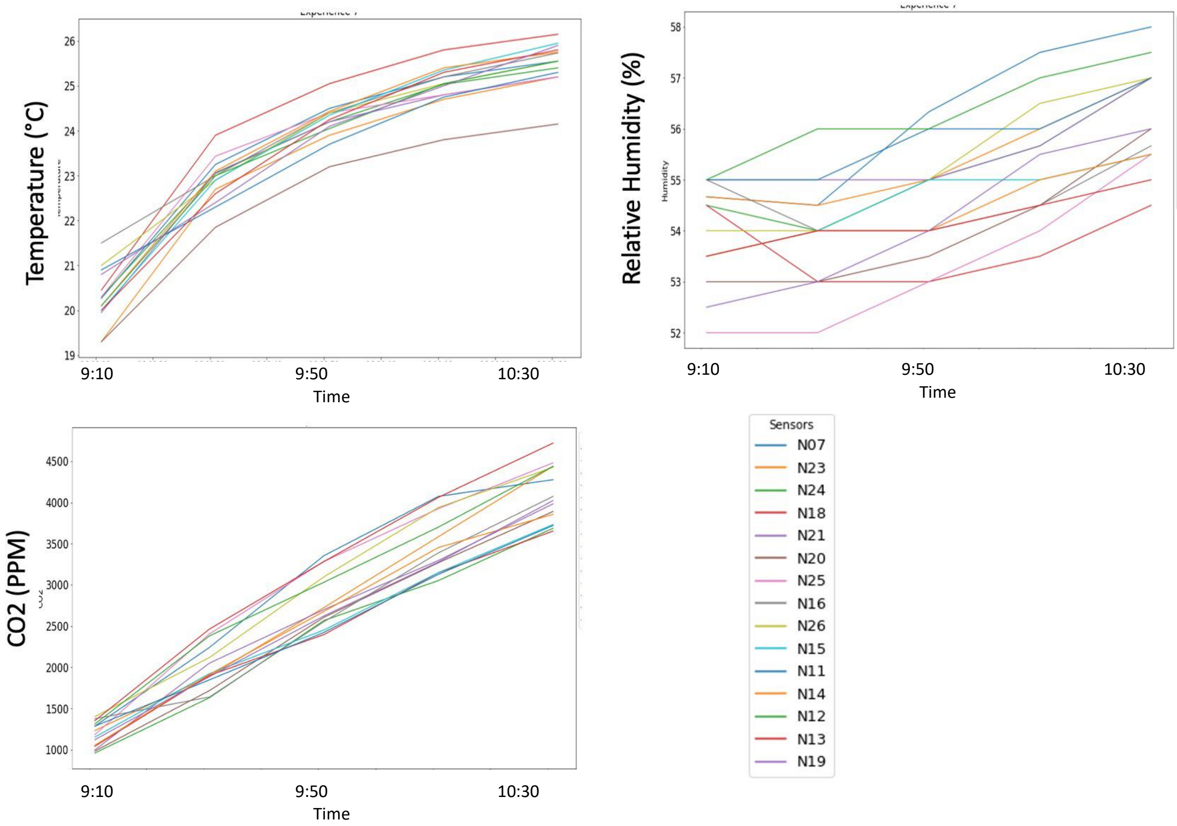

Figure 2.2 Variation of the temperature, relative humidity, and CO2 (Experiment 1)

Figure 2.3 shows the temperature, humidity, and CO2 heat map at the beginning and end of the class. Table 2.4 summarizes the statistical parameters of the comfort parameters. At the beginning of the class, the temperature varies between 19.3 °C and 21.5 °C, with an average value of 20.3 °C and a standard deviation of 0.6 °C. At the end of the class, it varies between 24.2 °C and 26.2 °C with an average value of 25.5 °C and a standard deviation of 0.5. The relative humidity varies at the beginning of the class between 52.0 % and 55.0 %, with an average value of 54% and a standard deviation of 0.98 %. At the end of the class, it varies between 54.5 % and 58.0%, with an average value of 56.3 % and a standard deviation of 1.0 %. Figure 2.4 shows the values of the comfort parameters at the beginning and end of the class in the Givoni bioclimatic chart (Givoni 1969). The green color indicates the comfort area in buildings. At the beginning of the class, all the monitoring locations are situated in the comfort area. At the end of the class, 14 of the 15 locations in the class are moderately outside the comfort area.

Finally, the CO2 concentration varies at the beginning of the class between 960 ppm and 1402 ppm, with an average value of 1182 ppm and a standard deviation of 151 ppm. At the end of the class, the CO2 concentration varies between 3652 ppm and 4720 ppm. Since the CO2 level mostly exceeds 1000 ppm during the class, it could cause students to have a dry cough and rhinitis (Haddad et al., 2021).

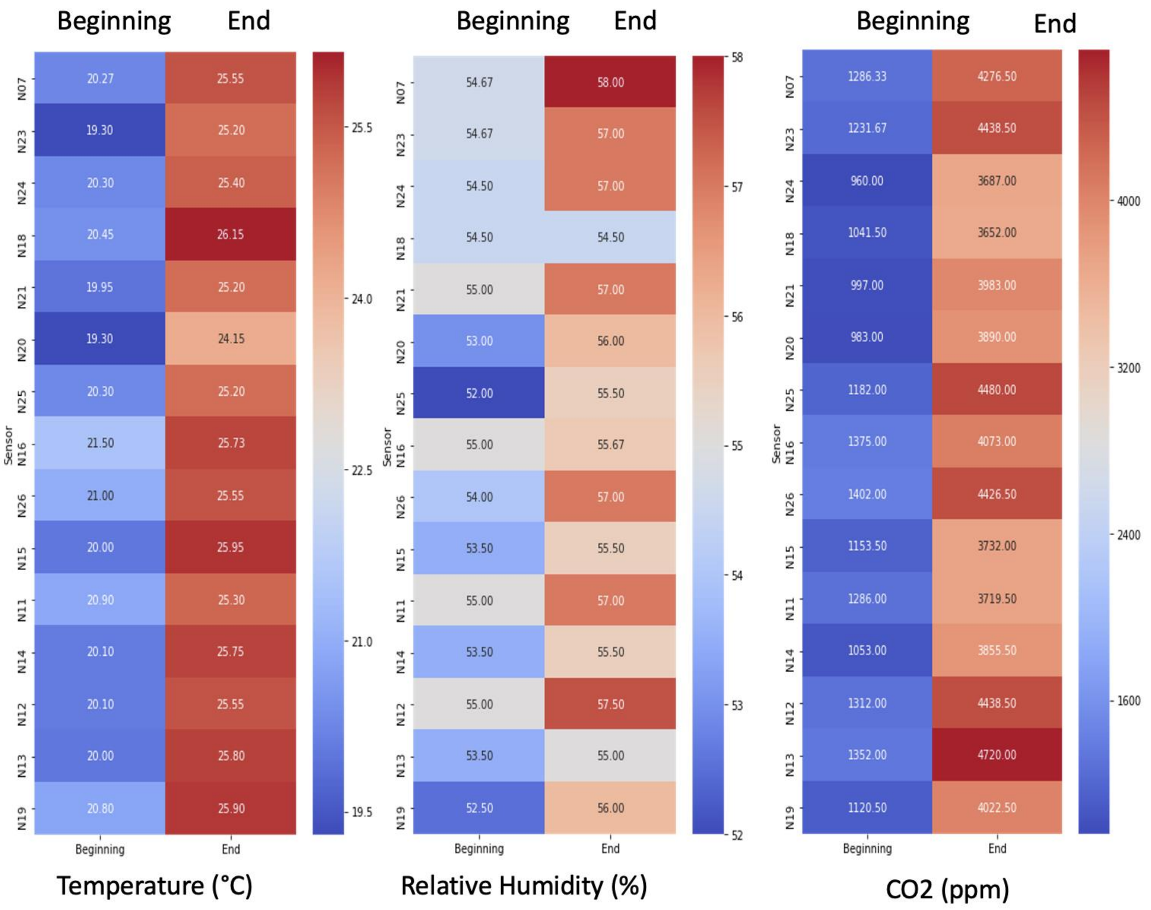

Figure 2.3 Heat maps of the spatial variation of the comfort parameters (Experiment 1)

Table 2.4 Statistical parameters of the comfort conditions (Experiment 1)

	Beginning			End		
	Temperature (° C)	Humidity (%)	CO2 (ppm)	Temperature (° C)	Humidity (%)	CO2 (ppm)
Minimum	19.3	52.0	960.0	24.2	54.5	3652
Maximum	21.5	55.0	1402	26.2	58,00	4720
Average	20.3	54.0	1182	25.5	56.3	4093
Standard Deviation	0.59	0.98	151.1	0.47	1.0	345

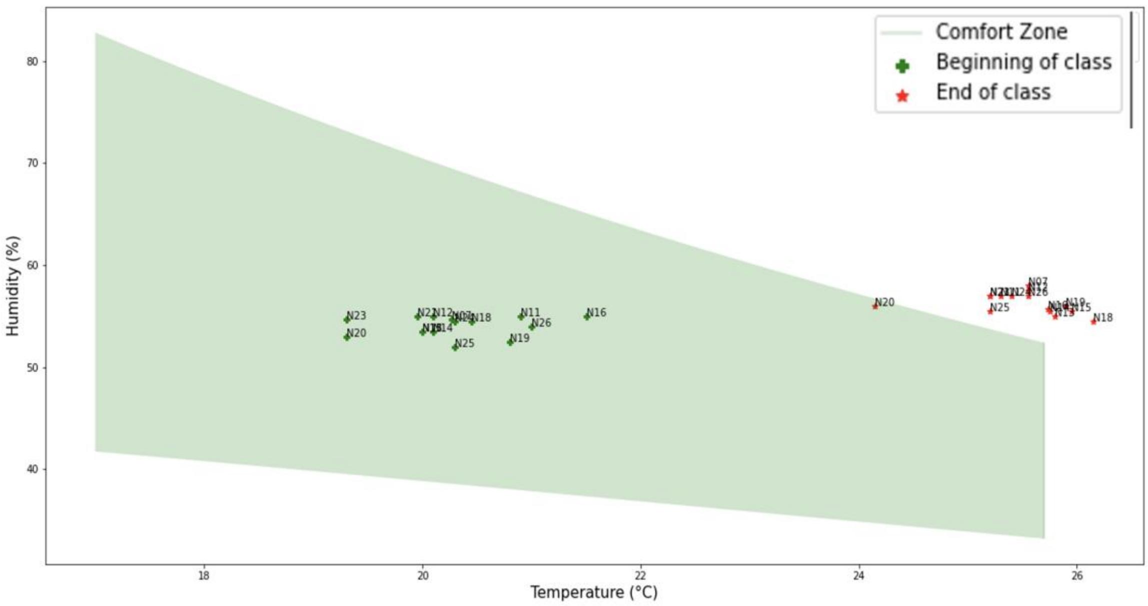

Figure 2.4 Recorded temperature and humidity in Givoni bioclimatic chart (Experiment 1)

Table 2.5 provides the spatial variation index (SVI) of the class's comfort parameters at the beginning and end. This index is determined as follows:

$$\text{SVI (parameter)} = \frac{\text{Max (parameter)} - \text{Min (Parameter)}}{\text{Average (parameter)}}$$

Humidity has the lowest spatial variation index, which is about 0.06 at the beginning and end of the class. CO2 has the highest SVI, which is equal to 0.37 at the beginning of the class, then decreases to 0.26 at the end of the class. SVI for the temperature equals 0.11 at the beginning of the class and 0.08 at the end of the class. Results show that the activity in the class leads to a reduction of the spatial variation of the comfort parameters.

Table 2.5 Spatial variation index (SVI) of the comfort parameters

Beginning of the class			End of the class		
Temperature	Humidity	CO2	Temperature	Humidity	CO2
0.11	0.055	0.37	0.078	0.062	0.26

2.3.1.2 Analysis of students' assessment of the comfort condition and learning efficiency

Figure 2.5 shows the relationship between the students' evaluation of the temperature and humidity and recorded values. At the beginning of the class, most students gave a high satisfaction score (4 or 5) for temperature and humidity. Only 3 students gave a medium score (3) to the temperature, and 2 gave a low score (2 or 3) to the humidity. At the end of the class, 8 students gave a medium score to the temperature comfort, indicating degradation in the temperature comfort during the class. The students' satisfaction from humidity remained constant.

Figure 2.5 shows a weak correlation between the students' evaluation of the temperature and humidity and recorded values. The correlation coefficient between the students' assessment of the temperature comfort and recorded values at the beginning and end of the class is equal to -0.22 and -0.25, respectively. The correlation coefficient between the humidity assessment and recorded values at the beginning and end of the class is equal to -0.059 and 0.18, respectively. This result indicates a weak correlation between the students' evaluation of the comfort conditions and measured values.

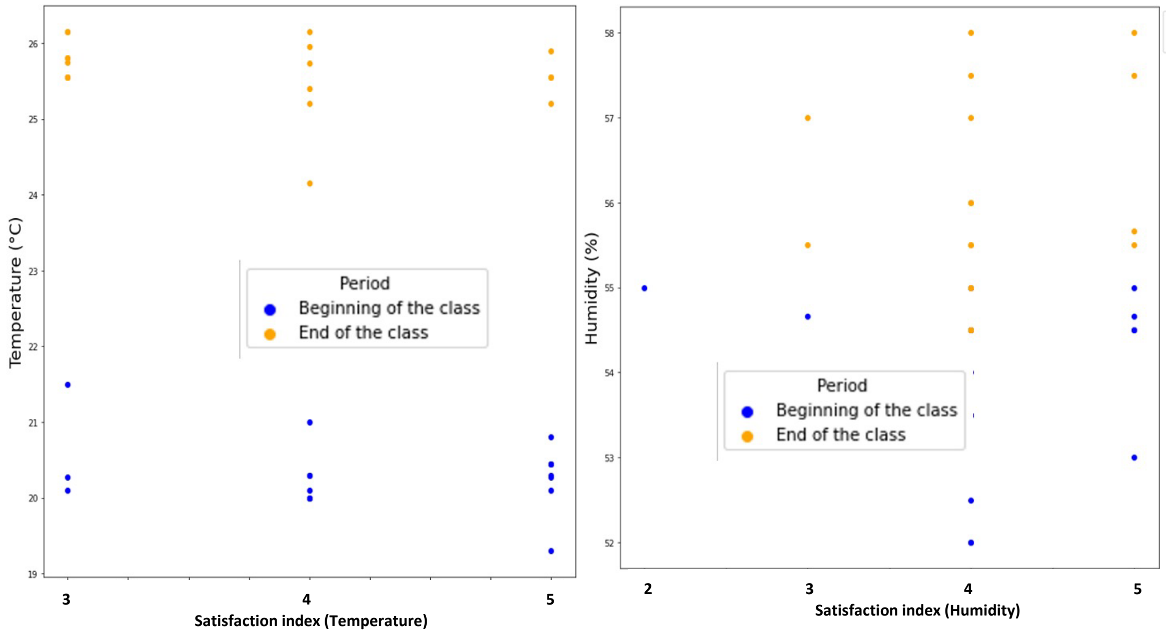

Figure 2.5 Relationship between the students' evaluation of the comfort parameters and recorded values (Experiment 1)

Table 2.6 summarizes the students' assessment of the learning efficiency (LE). It shows a high LE score at the beginning of the class. For example, 17 students gave a high score for LE, while only one gave a medium score. However, the LE score dropped significantly at the end of the class: 12 students scored high, while 6 gave a medium score. Figure 2.6 shows the relationship between recorded comfort parameters and LE. This figure does not reveal specific trends between measured parameters and students' assessment of the comfort conditions. Table 2.7 provides the coefficient of correlation between LE and recorded comfort parameters. It indicates a weak correlation between LE and recorded comfort conditions. However, since the p-value is higher than 0.05, there is insufficient evidence to confirm this weak correlation.

Table 2.6 Learning Efficiency scores (Experiment 1)

Qualitative Score	Low		Medium	High	
Quantitative Score	1	2	3	4	5
Beginning of the class			1	7	10
End of the class			6	9	3

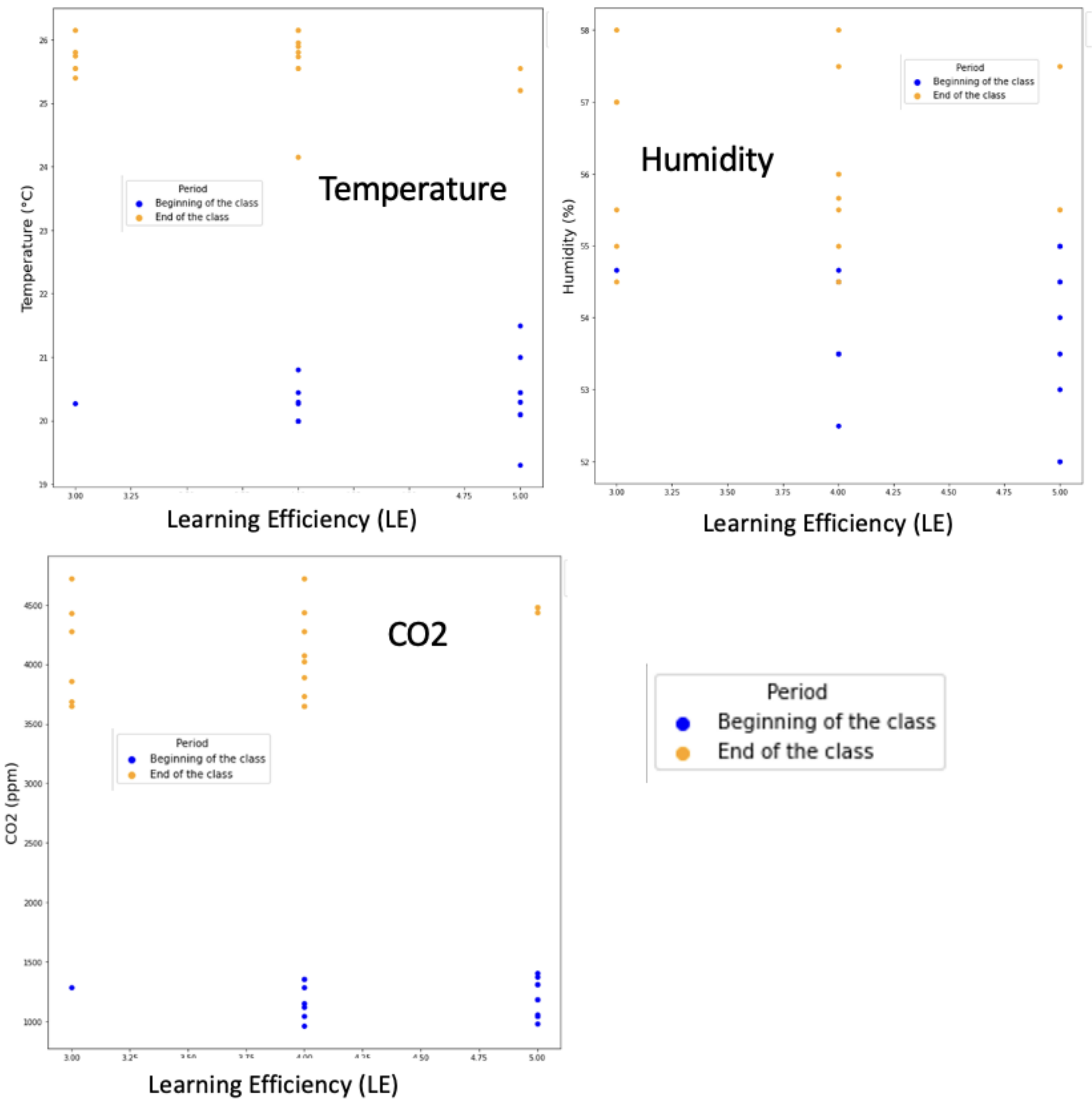

Figure 2.6 Relationship between Learning Efficiency (LE) and comfort recorded values (Experiment 1)

Table 2.7 Correlation coefficient between LE and recorded comfort parameters (Experiment 1)

Class	Temperature	Humidity	CO2
Beginning	0.1 p-value = 0.68	0.2 p-value = 0.68	-0.078 p-value = 0.75
End	-0.25 p-value = 0.31	-0.033 p-value = 0.89	0.26 p-value = 0.29

Figure 2.7 depicts the relationship between LE and the students' assessment of the comfort conditions. At the beginning of the class, we observe a good agreement between LE and the comfort conditions assessment. At the end of the class, LE fits better with the temperature than with the humidity.

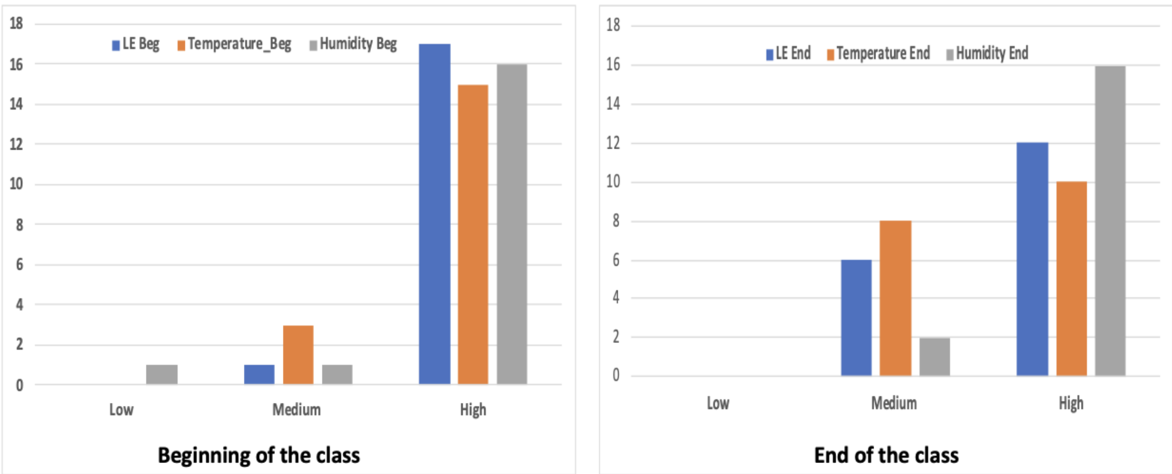

Figure 2.7 Relationship between LE and the students' evaluation of comfort conditions

2.3.2 Results of Experiment 2

2.3.2.1 Analysis of recorded comfort conditions

Experiment 2 was conducted in classroom 2, December 4, 2019, in the morning. The mean outdoor temperature and relative humidity were 2.8 °C and 94%, respectively. The classroom windows were opened only during the coffee break (10:20 - 10:40 am). 20 students attended this class.

Figure 2.8 shows the variation of the indoor parameters. It includes three phases. The first phase corresponds to an increase in temperature, humidity, and CO2. The second phase corresponds to the coffee break, with a general decrease in these parameters. This reduction is related to a decrease in the students' number in the classroom and windows opening. The last phase corresponds to the second part of the class, with a re-increase in the comfort parameters due to the class activity. The temperature varies between 20.2 °C and 25.85 °C. It exceeds the temperature threshold limit value in public buildings in France, which is equal to 19 °C. The relative humidity varies between 39.5 % and 56.0 %. The CO2 indicates the highest variation: it increases from 570 ppm to values exceeding 5000 ppm. This high level of CO2 could disturb students (Haddad et al 2021).

The impact of the window opening during the coffee break depends on the sensor location. The highest impact concerns sensors close to windows with a decrease of 1.65 °C in the temperature, 1.5 % in the relative humidity, and 1180 ppm in the CO2 concentration. The lowest variation concerns sensors far away from windows with a decrease of 0.4 °C in the temperature, 0.5 % in the relative humidity, and 674 ppm in the CO2 concentration. However, the impact of the windows opening vanishes after around 50 minutes. The comfort parameters recover the variation trends before windows opening.

Figure 2.9 shows the heat map of the temperature, humidity, and CO2 at the beginning and end of the class. Table 2.8 summarizes the statistical parameters of these parameters. At the beginning of the class, the temperature varies between 20.2 °C and 21.9 °C, with an average value of 20.9 °C and a standard deviation of 0.51. At the end of the class, the temperature varies between 21.1 °C and 25.5 °C, with an average value of 24.4 and a standard deviation of 0.84. The relative humidity varies at the beginning of the class between 39.5% and 46.0 %, with an average value of 43.2% and a standard deviation of 1.63%. At the end of the class, it varies between 47.5 % and 54.0%, with an average value of 51.2 % and a standard deviation of 1.7%. Figure 2.10 shows the comfort parameters in Givoni bioclimatic chart. It could be observed that the different locations in the classroom at the beginning and end of the class remain in the comfort area.

Finally, the CO2 concentration varies at the beginning of the class between 570 ppm and 2180 ppm, with an average value of 1548 ppm and a standard deviation of 404 ppm. At the end of the class, the CO2 concentration varies between 2523 ppm and 5000 ppm. The latter is equal to the high limit of the device range, which means that the CO2 concentration at the end of the class exceeds 5000 pm.

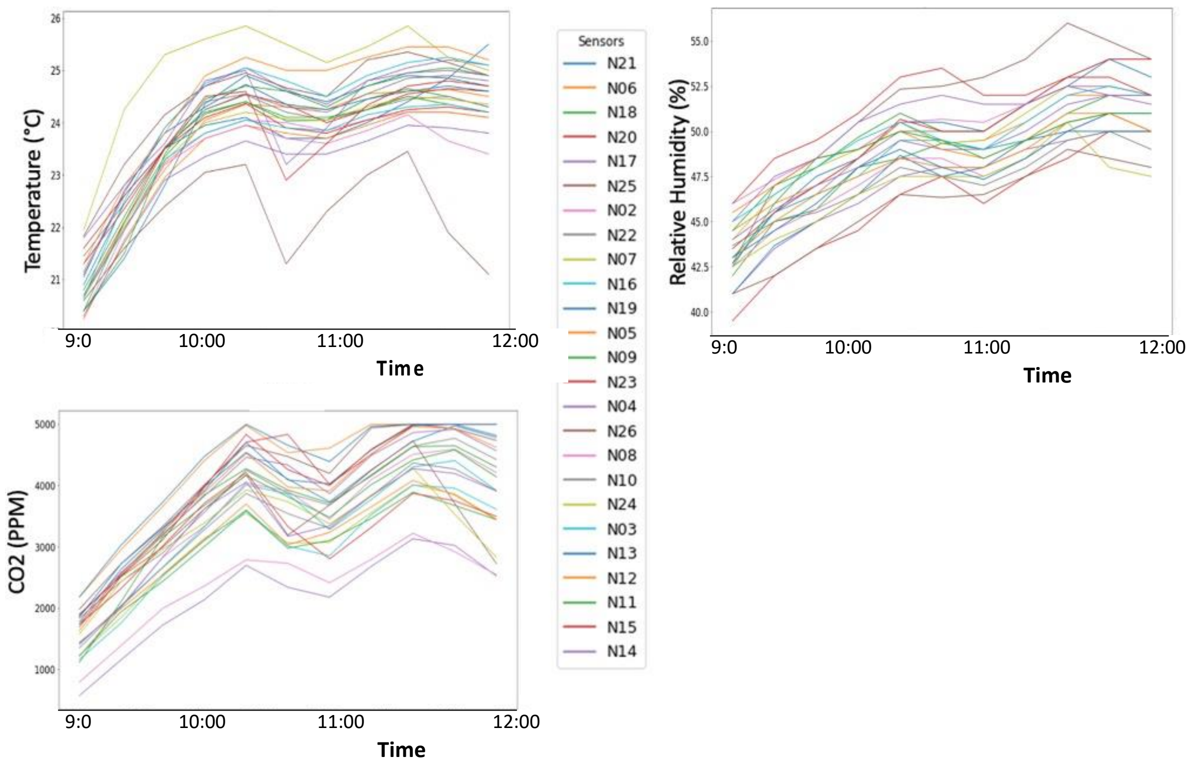

Figure 2.8 Variation of recorded values of the indoor comfort parameters (Experiment 2)

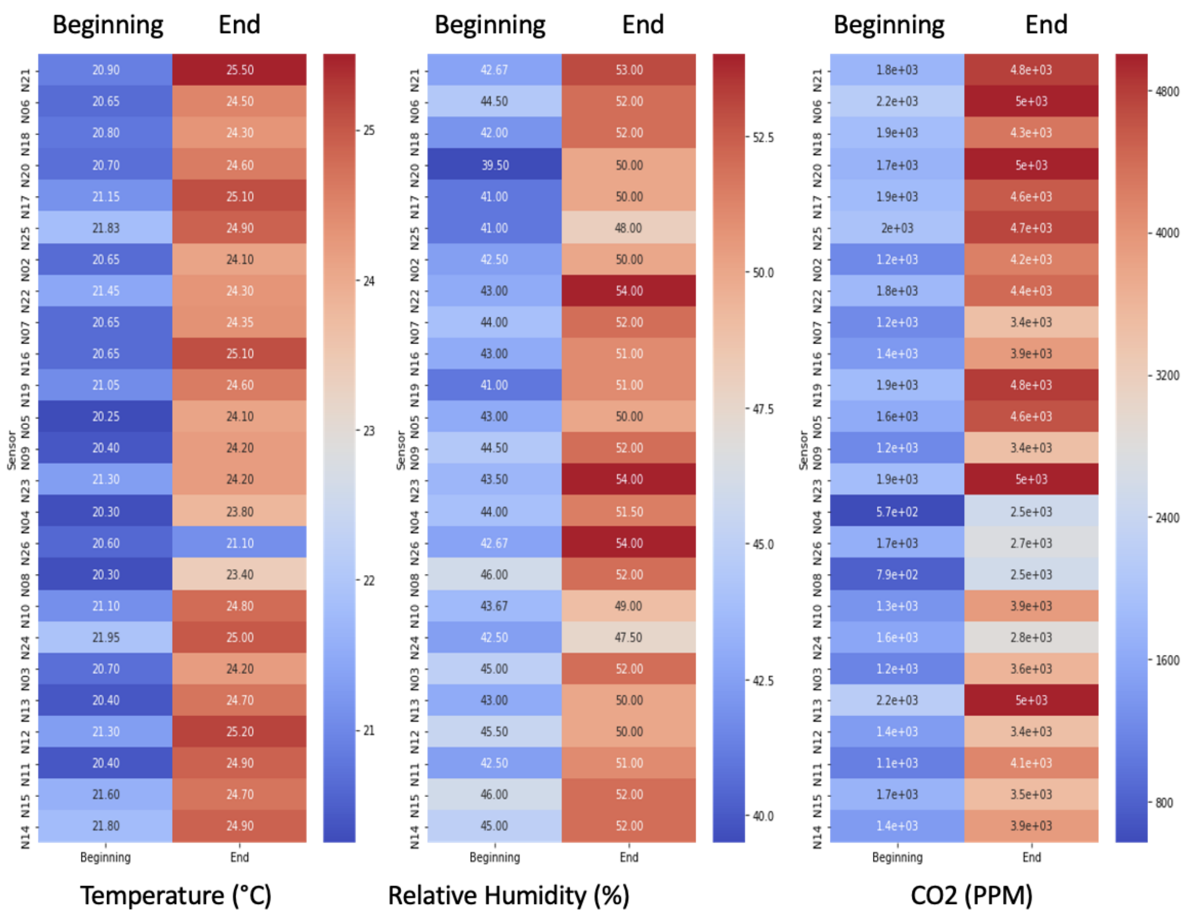

Figure 2.9 Heat maps of the spatial variation of the comfort parameters (Experiment 2)

Table 2.8 Statistical parameters of the comfort conditions (Experiment 2)

	Beginning			End		
	Temperature (° C)	Humidity (%)	CO2- (ppm)	Temperature (° C)	Humidity (%)	CO2 (ppm)
Minimum	20.2	39.5	570	21.1	47.5	2523
Maximum	21.9	46.0	2180	25.5	54.0	5000
Average	20.9	43.2	1548	24.4	51.2	4016
Standard Deviation	0.51	1.63	404	0.84	1.7	803

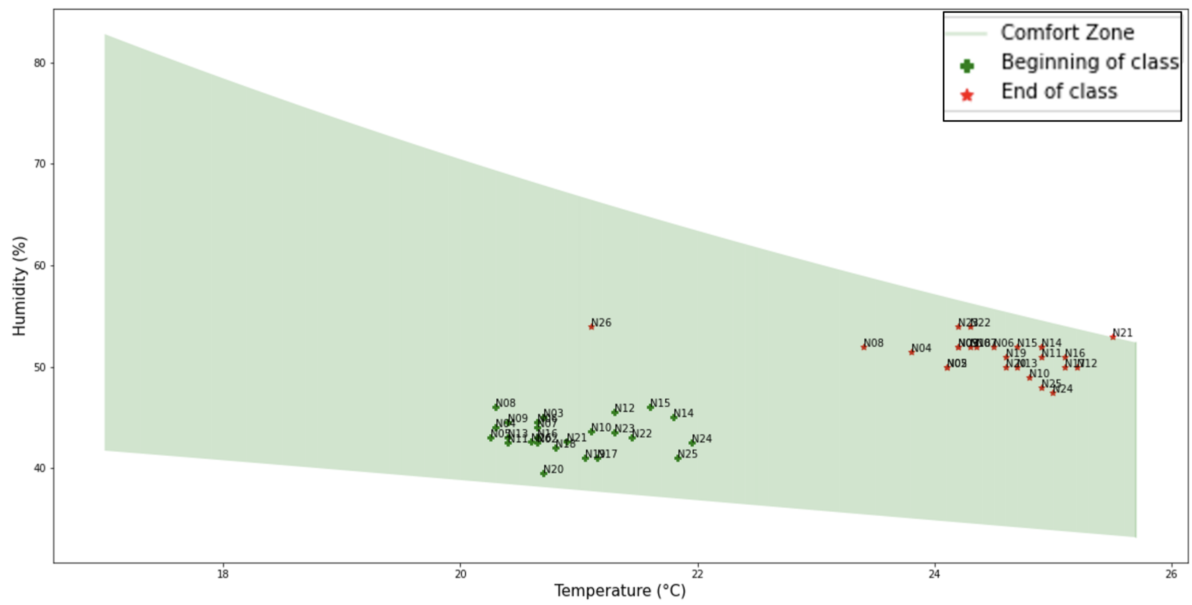

Figure 2.10 Recorded temperature and humidity in Givoni bioclimatic chart

Table 2.9 provides the spatial variation index (SVI) of the class's comfort parameters at the beginning and end. Humidity has the lowest index, which is about 0.15 at the beginning and 0.13 at the end of the class. The CO2 has the highest SVI, which is equal to 1.04 at the beginning of the class, then decreases to 0.62 at the end of the class. The SVI for the temperature is equal to 0.08 at the beginning of the class and 0.18 at the end of the class. These results indicate an important spatial variation of the comfort parameters at the beginning and end of the class.

Table 2.9 Spatial variation index of the comfort parameters (Experiment 2)

Beginning of the class			End of the class		
Temperature	Humidity	CO2	Temperature	Humidity	CO2
0.08	0.15	1.04	0.18	0.13	0.62

2.3.2.2 Analysis of students' evaluation of the comfort condition and Learning Efficiency

Figure 2.11 and Table 2.10 illustrate the relationship between the students' assessment of the temperature and humidity and recorded values. At the beginning of the class, 17 students gave a high score for the temperature, and 3 gave a medium score, while 13 students gave a high score for humidity, 6 gave a medium score, and one a low score. At the end of the class, students gave lower scores for temperature and humidity. The number of students who gave a high score for the temperature dropped from 17 to 12. For humidity, this number dropped from 13 to 9.

Figure 2.11 indicates a weak correlation between students' assessment of the temperature and humidity and recorded values. The correlation coefficient between the students' assessment of the temperature comfort and recorded value at the beginning and end of the class is equal to -0.024 and -0.021, respectively. For humidity, the correlation coefficient between the students' evaluation and recorded values at the beginning and end of the class is equal to 0.48 and -0.18, respectively. Globally, results show a weak correlation between the students' evaluation of the comfort parameters and recorded values.

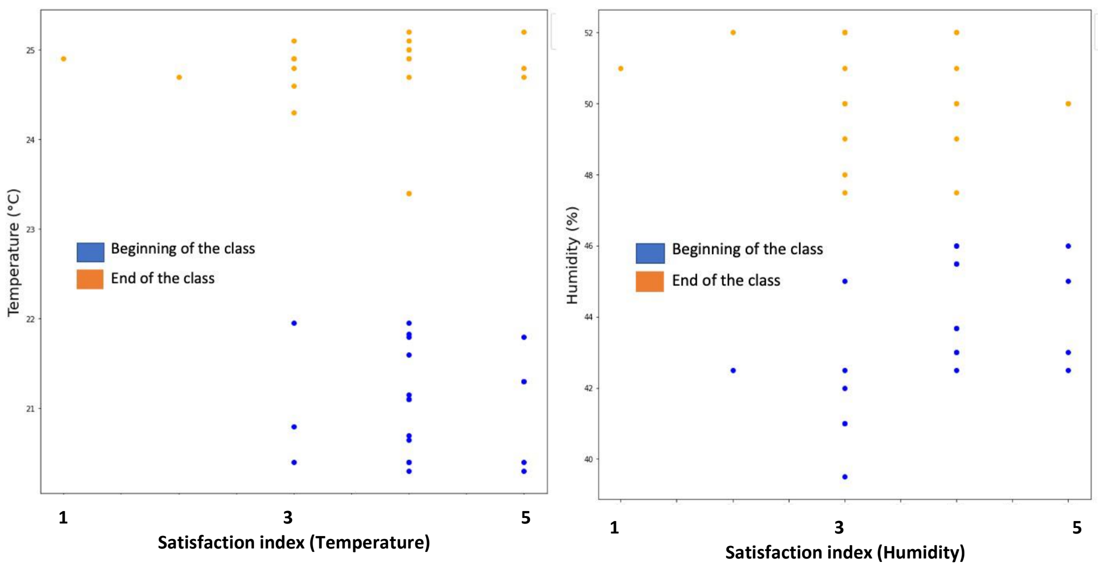

Figure 2.11 Relationship between scores attributed to comfort parameters and recorded values (Experiment 2)

Table 2.10 Scores attributed to comfort temperature and humidity (Experiment 2)

Qualitative Score	Low		Medium	High	
Quantitative Score	1	2	3	4	5
Temperature Beginning			3	12	5
Temperature End	1	1	6	9	3
Humidity Beginning		1	6	9	4
Humidity End	1	1	9	7	2

Table 2.11 summarizes the learning efficiency (LE). At the beginning of the class, 14 students gave a high score for LE, 5 gave a medium score, and the only one showed a low score. At the end of the class, LE dropped significantly: only 8 students gave a high score, 4 gave a medium score, and 8 gave a low score.

Figure 2.12 shows the relationship between LE and recorded values of comfort parameters. This figure does not reveal specific trends between LE and recorded values. Table 2.12

indicates a low correlation between LE and the recorded values. However, since the p-value is higher than 0.05, there is insufficient evidence to confirm this weak correlation.

Table 2.11 Learning Efficiency scores (Experiment 2)

Qualitative Score	Low		Medium	High	
Quantitative Score	1	2	3	4	5
Beginning of the class	1	0	5	10	4
End of the class	2	6	4	8	0

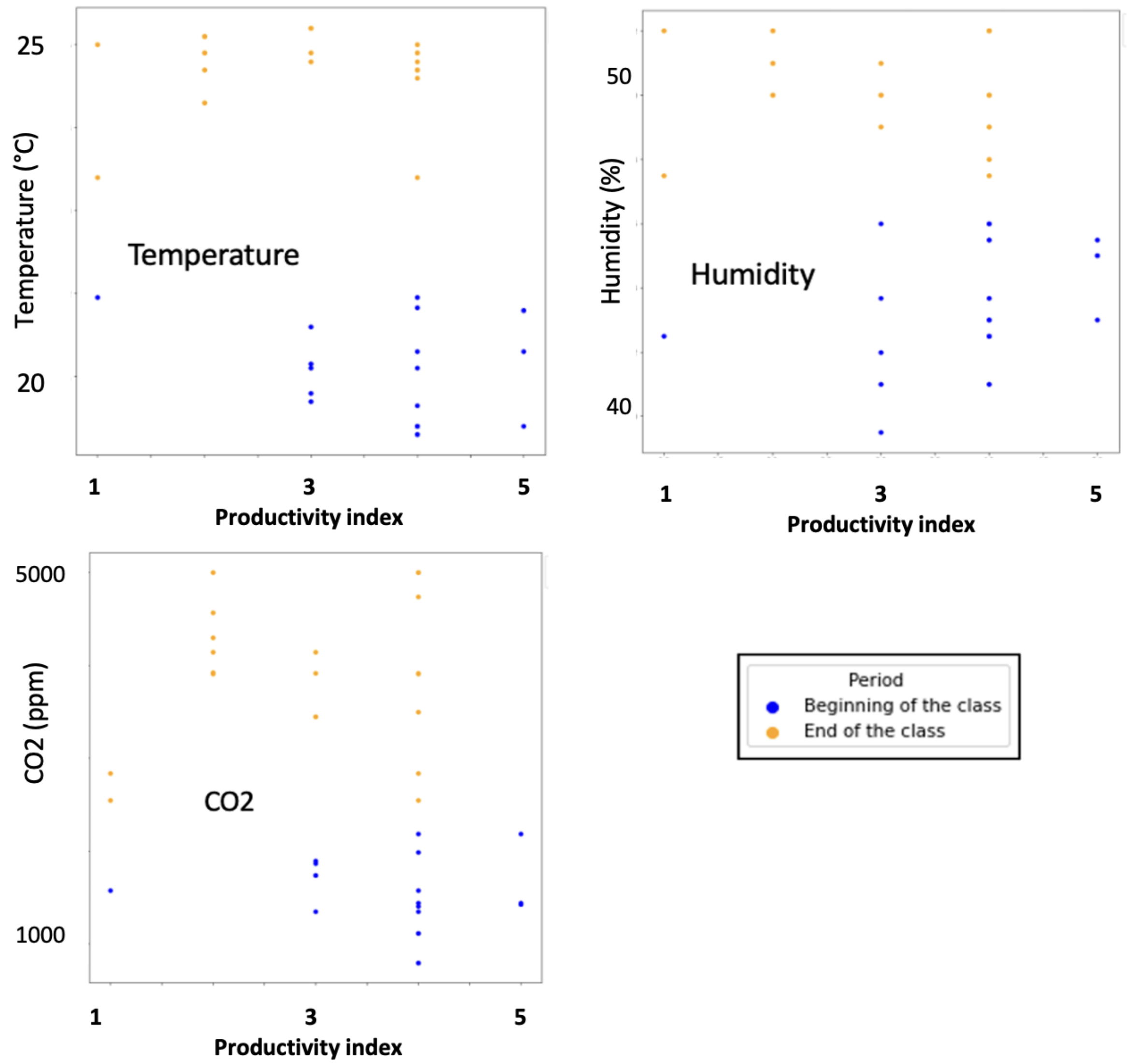

Figure 2.12 Relationship between the students' productivity and the recorded values of comfort parameters (Experiment 2)

Table 2.12 Correlation coefficient between Learning Efficiency and recorded comfort parameters (Experiment 2)

Class	Temperature	Humidity	CO2
Beginning	-0.15 p-value = 0.52	0.37 p-value = 0.10	-0.11 p-value = 0.65
End	0.064 p-value = 0.79	0.13 p-value = 0.59	0.16 p-value = 0.49

Figure 2.13 depicts the relationship between LE and the students' assessment of the comfort conditions. At the beginning of the class, we observe a good agreement between these parameters. However, at the end of the class, we observe a general decrease in the students' satisfaction, particularly for LE: The number of students giving a low score for LE increases from 1 to 8, while for humidity, it increased from 1 to 2 and for temperature from 0 to 2. Thus, the poor score for LE at the end of the class could be related to students' fatigue.

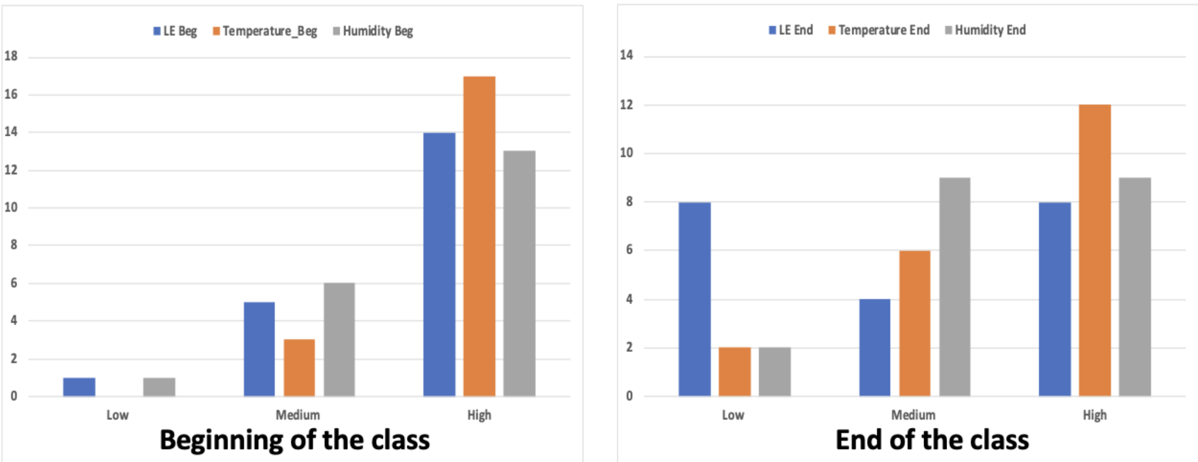

Figure 2.13 Relationship between LE and students' assessment of comfort conditions (Experiment 2)

2.3.3 Results of 5 experiments

This section presents the outcome of the results of the five experiments conducted in this research. Details about these experiments are given in table 2.3.

Table 2.13 provides the correlation coefficient and p-value between learning efficiency and recorded comfort parameters. It shows a weak correlation between LE and recorded values. According to p-values, the significance of this weak correlation is confirmed at the end of the class (p-value < 0.05).

Table 2.14 provides the correlation coefficient between LE and the students' assessment of temperature and humidity comfort. At the beginning of the class, the correlation coefficient exceeds 0.65 (p-value < 0.05), which means that the LE is related to the students' perception of the comfort conditions. At the end of the class, the correlation coefficient is inferior to 0.13 (p-value < 0.05), which means that the perception of the comfort conditions does not impact the students' learning efficiency. In general, at the end of the class, the learning efficiency is influenced by the students' fatigue.

Table 2.13 Correlation coefficient between learning efficiency and recorded comfort parameters (5 experiments)

Class	Temperature	Humidity	CO2
Beginning	0.23 p- value = 0.06	0.077 p- value = 0.63	0.005 p- value = 0.96
End	0.064 p- value = 0.00	0.13 p- value = (0.037	0.16 p- value = 0.00

Table 2.14 Correlation coefficient between learning efficiency and the students' assessment of comfort parameters (5 experiments)

Class	Temperature score	Humidity score
Beginning	0.6 p- value = 0.00	0.65 p- value = 0.00
End	0.064 p- value = 0.00	0.13 p- value = 0.00

2.4 Conclusion

This chapter presented an experimental investigation of the impact of the indoor classroom environment on students' learning efficiency. The research included both comfort parameters monitoring at the students' desks and a questionnaire about the students' assessment of the comfort conditions and learning efficiency.

Results showed a significant spatial variation in the indoor comfort conditions, particularly for the temperature and CO2 concentration. The class activity generally causes a decrease in the spatial variation amplitude at the end of the class. Results showed that the temperature could exceed up to 5 °C, the temperature threshold limit value in public buildings in France. Better control of the heating equipment is necessary for both energy savings and indoor thermal comfort.

The impact of the windows opening during the coffee break leads to a significant decrease in the temperature and CO2 in particular in areas close windows, however the effect. However, the impact of the windows opening vanishes after around 50 minutes.

At the beginning of the class, results show a significant correlation between learning efficiency and the students' assessment of comfort conditions. At the end of the class, results show a weak correlation with both recorded comfort parameters and the students' assessment of the indoor conditions. This result could be attributed to students' fatigue at the end of the class.

This result indicates that the learning efficiency decreases during the class. However, students do not mainly attribute this decrease to the degradation in the indoor conditions.

As a result of this research, it is recommended to install a ventilation system in the classroom to reduce the amplitude of the variation of the indoor conditions and improve comfort conditions. In the absence of this system, it is recommended to open the classroom windows regularly.

The main limitation of this research is related to the small size of classes. This study should be extended to larger classes in the future. A second limitation is associated with the absence of a ventilation system. Future studies should investigate the impact of ventilation on both students' comfort and learning capacity.

In the following chapter, we will investigate how smart monitoring of social housing has provided insights into energy consumption and indoor comfort. The experiment is based on the monitoring of 13 social housing units in the North of France.

3 Chapter 3: Experimental analysis of Indoor environmental quality and energy consumption in social housing units

A paper based on this chapter is under preparation for an international Journal.

3.1 Introduction

Over the past decades, an intensive research activity has been devoted to smart buildings, communities, cities and infrastructure (D. Minol 2017). This activity aimed at providing reliable and energy efficient services without compromising the level of comfort of occupants. It also aimed at making the buildings more intelligent to enhance both the quality of services to citizens and to reduce building energy consummation and related green gashouse emissions. Indeed, the building sector is responsible of about 39.2% of final energy consumption in Europe according to Eurostat and 40% globally with a contribution of 30% of the total CO2 emissions (W.Ahmad et al 2016 ,P. H. Shaikh et al 2014).

The quality of the indoor environment has a significant impact on the productivity and health of occupants (S.G. Navada et al 2013; J.-H CHOI et al 2016). Aa a consequence, the Indoor comfort and its impact on the occupants' health became an emerging area of research (Awada et al 2020). Some scholars investigated the satisfaction and thermal comfort in the social housings (Rodriguez.G et al (2019, Serrano-Jiménez, A. et al (2020), Tubelo, R et Al (2021)). Rodriguez.G et al (2019) used qualitative data such as occupants' surveys and quantitative data such as data loggers to investigate the level of comfort and occupants' satisfaction in social housing residences in Bogota, Colombia. Collected data showed occupants' dissatisfaction from the indoor comfort. Serrano-Jiménez, A. et al (2020) analyzed the indoor comfort parameters of three social building occupied by elderly people. They monitored the temperature, humidity and CO_2 of the living room and the bedroom. The results showed that the CO_2 concentration reached unhealthy levels for a long period of the day. In addition, the values of temperature and humidity did not respect the comfort requirements. While, Tubelo, R et Al (2021) developed a low-budget building envelope optimization method which can improve the indoor thermal conditions up to 76% in Brazil.

Occupants' daily habits has a direct impact on the energy consumption (Happle et al. 2018) and related CO_2 emissions (Monzón-Chavarrías et al. 2020). Harputlugil, G. U et al (2019) studied the impact of occupant's behavior on energy consumption in Turkey. They established occupants' profiles based on the sensitivity analysis. Delzendeh, E. et al (2017) and Balvedi, B. F et al. (2018) presented a literature review on the impact of occupants' behavior using both monitoring and modeling data.

Colic-Damjanovic et al. (2021) presented the benefits and difficulties of implementation energy efficiency measures in the social housing sector in Serbia as a part of a strategy towards sustainability, energy affordability and environmental benefits. While Lee, J et al (2020) investigated the use of the solar photovoltaic energy as a solution for low-income social houses in Korea.

This chapter presents how the use of a smart monitoring of social housing units helped in understanding the energy consumption and the indoor comfort. The research is based on monitoring 13 social housing apartments in the North of France. The monitoring included indoor comfort (temperature and humidity), the total energy consumption as well as the energy consumptions related to heating, hot water and lighting. It also included the hot water consumption.

3.2 Methodology and materials

3.2.1 Overview

This research is based on monitoring 13 social housing appartements in the North of France. The apartments were selected according to the floor level and orientation. Table 3.1 provides the area and orientation of the apartments. Their area varies between 45 m^2 and 95 m^2. Five appartements are located in the ground floor, three in the first floor and five in the 2^{nd} floor. Six apartments are oriented to the West, five to the East, and two to the North. The number of occupants varies between 1 and 7.

Table 3.1 Characteristics of the monitored apartments

Apartment	Surface Area (m^2)	Orientation
A1	80	West
A2	95	East
A3	65	North
A4	45	North
A5	80	West
A6	95	East
A7	65	East
A8	80	West
A9	45	West
A10	80	West
A11	45	West
A12	95	East
A13	65	East

The monitoring program is illustrated in Figure 3.1. It includes a set of sensos to follow (i) the comfort conditions (temperature and humidity), (ii) the heating system in the living room and the bedroom, (iii) the energy consumptions related to the hot water and lighting system, and (iv) the hot water consumption.

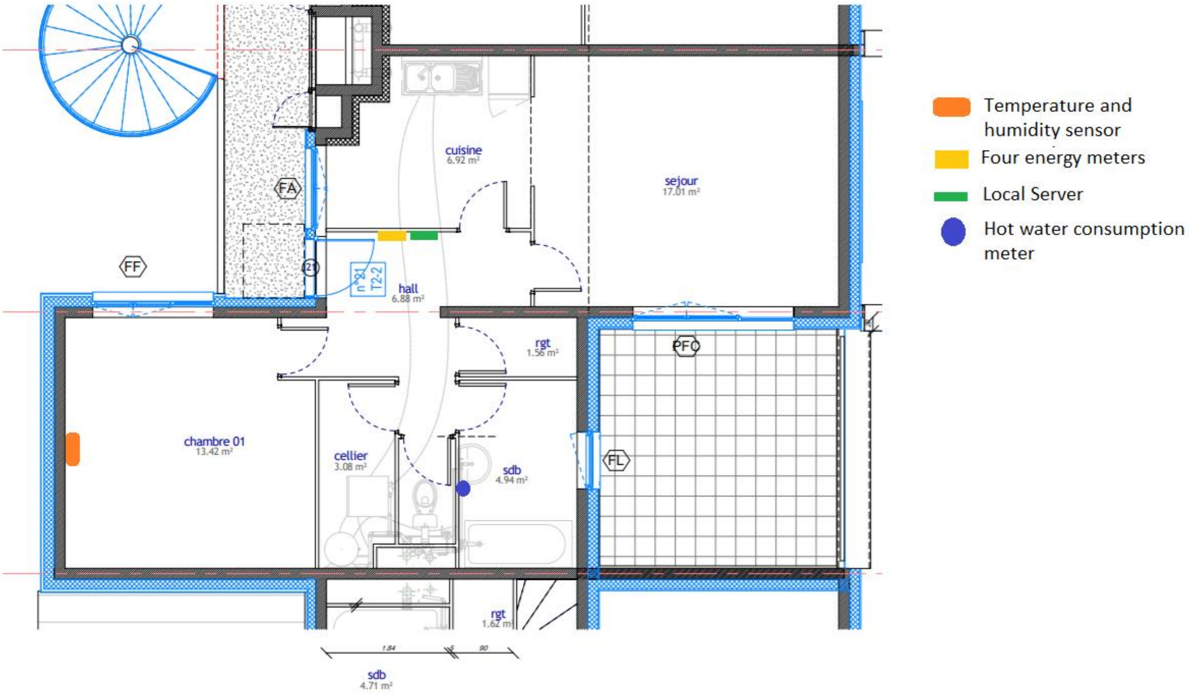

Figure 3.1 Instrumented Building

3.2.2 Monitoring system

The monitoring system is based on a wireless sensor network containing sensors, a local server and a user interface. Data is stored in the local server. Occupants can access to real-time and historical data via a graphic interface. The monitoring system is composed of three modules: a set of sensors, a local server, and a user graphic interface.

3.2.2.1 Sensors

The monitoring system includes the following sensors:

- A temperature and Humidity sensor (TH) (Figure 3.2). This sensor is a panstamp chip-based sensor. It measures temperature and humidity using Si7021 sensor. It sends data every 10 minutes to the local server using the SWAP protocol. Table 3.2 shows the characteristics of the Si7021 sensor.

Figure 3.2 TH Sensor

Table 3.2 Characteristics of Si7021

	Measuring range	Precision
Temperature	-10°C to 85°C	± 0,4°C
Humidity	0 to 100%	± 3%

- A hot water sensor, which is based on the panstamp chip. It measures the consumption of hot water and it sends a message to the local server using the protocol SWAP. It uses the IZAR Pulse sensor to count the number of liters.

- The Eltako FWZ14) Electricity meter (Figure 2.3), which measures the electric energy consumption. Data is transmitted to the local server via enocean protocol.

Figure 3.3 Eltako FWZ14 (Electrical Energy consumption)

3.2.2.2 Local Server

The Home Local Server (Figure 2.4) is based on Raspberry pi 3, which is a powerful low-cost ARM based processor board. It is capable of performing functions like any computer with a reduced physical structure. It is equipped with Enocean and Panstamp receivers. The local server is based on nodejs and offers the following features:

- Data exchange with sensors
- Data organization in a semantic structure.
- Sensor errors detection
- Data visualization.

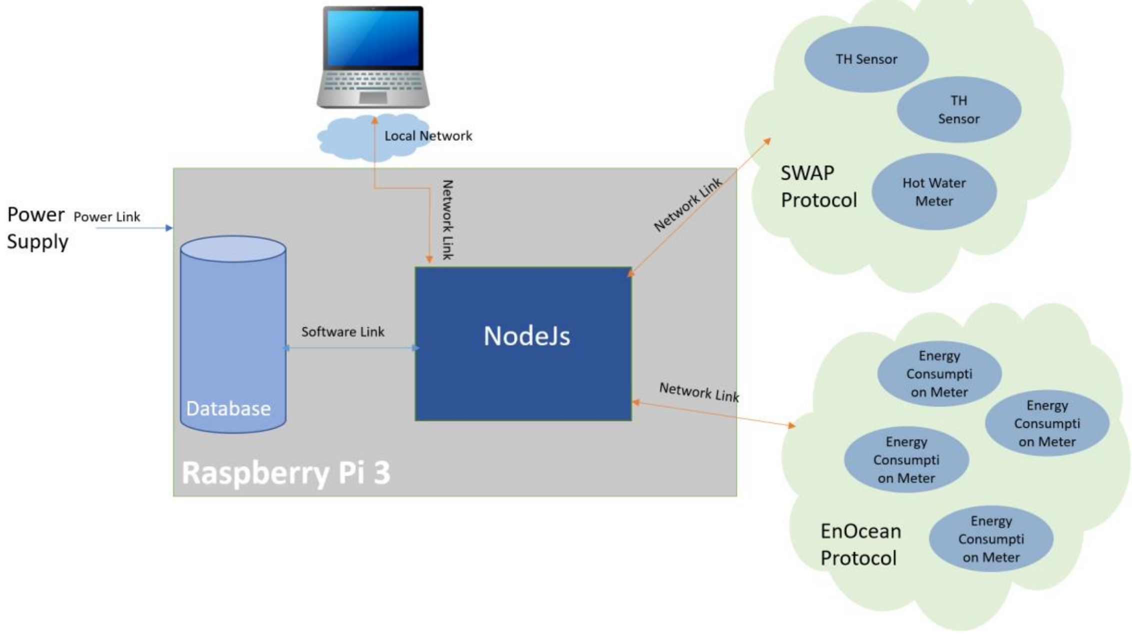

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Figure 3.4 Local server

3.2.2.3 User graphic interface

The user graphic interface was designed to enable an easy access and visualization of both real-time and historical data (Figure 3.5). The interface could be easily adapted to any change in the monitoring system such as adding or taking off a sensor.

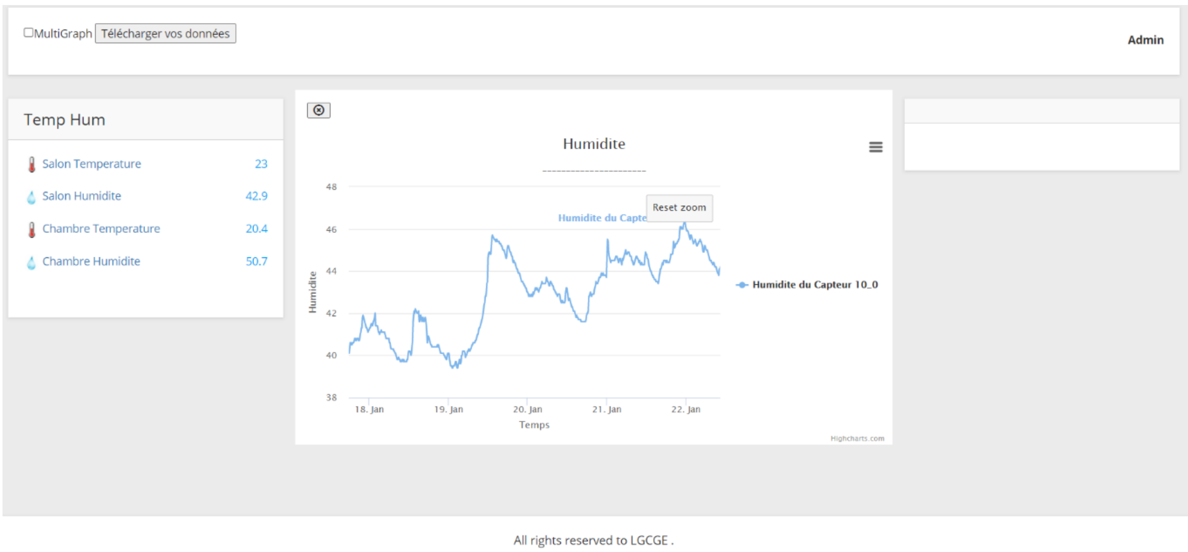

Figure 3.5 User's graphic interface

3.2.3 Monitoring program

Monitoring of comfort conditions and energy consumption was conducted during the summer season, between May 25 and October 17. The outdoor temperature ranged from 8.9°C to 26.9°C in the summer and from 2.1°C to 14.9°C between October 18 and February 8, the winter period.

Sensor data collection and cleaning was performed by the local server during the monitoring period; however, data analysis was performed during the laboratory. Figures 3.6 and 3.7 show the results of the data reception and cleaning during summer and winter season. Some data are missing due to sensor anomalies such as interference, battery discharge, or improper installation, especially for energy meters.

During the summer season, all sensors worked properly, except for the four sensors that were not installed due to the architecture of the apartment, e.g., apartment A9 contains only one living room, therefore we did not install the bedroom's sensors (temperature, humidity and heating). While in winter we lost the heating energy data of three apartments A8, A9 and A11.

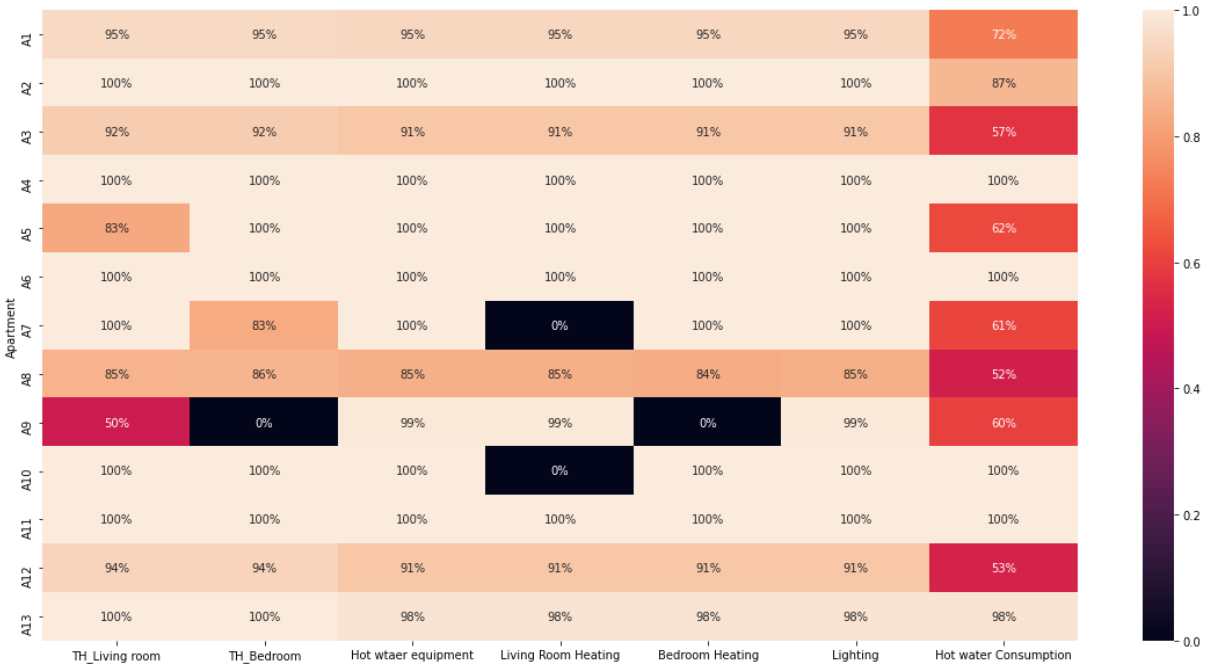

Figure 3.6 Data reception rate in summer

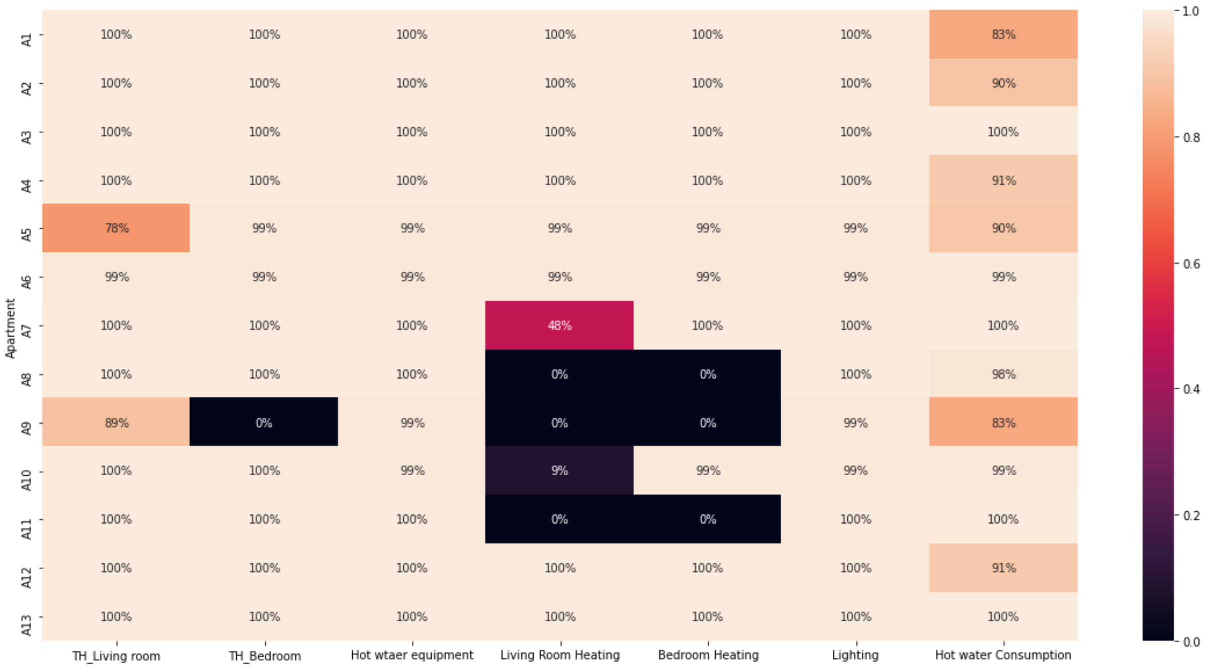

Figure 3.7 Data reception rate in winter

3.3 Results and Discussion

This section starts by a presenting and discussion of data recorded in Winter, then it presents data recorded in summer.

3.3.1 Winter season

Data was recorded during the period from October 18 to February 8.

3.3.1.1 Comfort conditions

The comfort conditions in the living room and bedroom in the instrumented housing units were recorded during in winter 2020. Figures 3.8 and 3.9 show an example of the temperature and humidity variation in one appartement. The indoor temperature varies between 19.1°C and 23. 2°C, while the humidity varies between 39.5% and 78.5%.

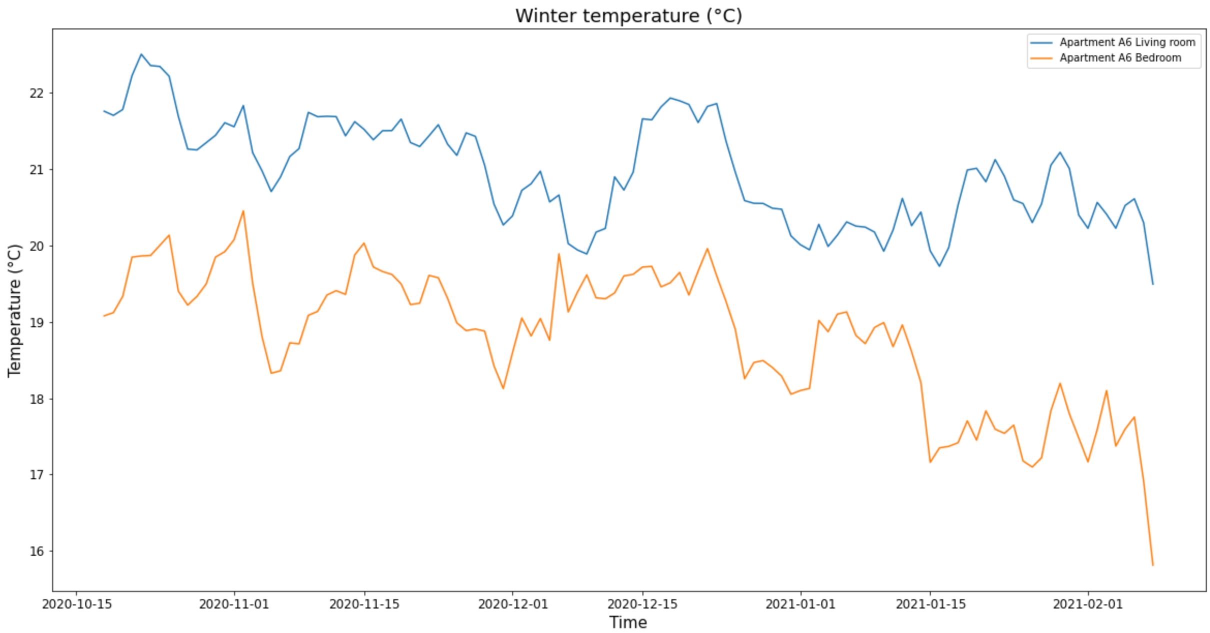

Figure 3.8 Variation of the temperature in Winter

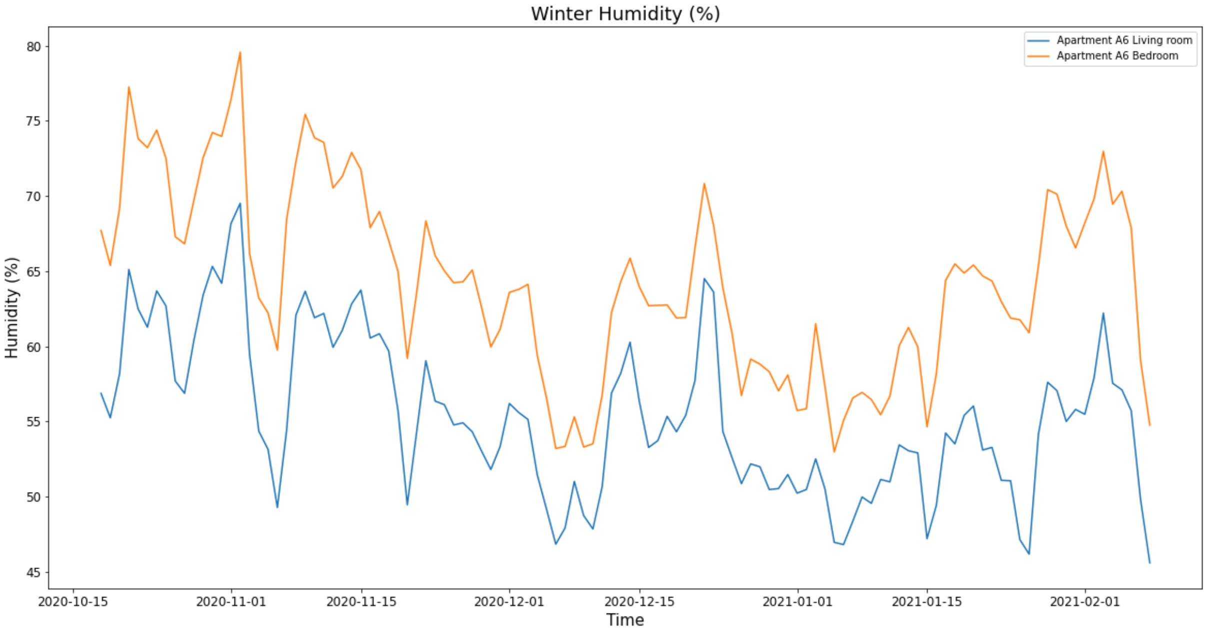

Figure 3.9 Variation of the humidity in winter

Table 3.3 shows the statistics of indoor comfort parameters. The highest (30°C) and lowest (11.5°C) temperatures were recorded by a first-floor, east-facing apartment A7 with an average temperature of 15.6°C, occupied by three people. The highest humidity (92%) was recorded in the west-facing first floor apartment of 45 m² with one occupant, while the lowest humidity (31.9%) was recorded in a north-facing second floor apartment. The average temperature ranged from 15.6°C to 21.4°C with a standard deviation of 1.7°C. while the average humidity was between 49% and 64.9% with a standard deviation of 4.42%. Table 3.3 also shows that the ground-floor apartments marked high humidity values such as apartment A9, A10, A6.

Table 3.3 Statistical parameters of the comfort conditions in winter

		A13	A21	A32	A41	A52	A67	A73	A83	A91	A106	A113	A124	A135
Tempera	Max	23.5	22.8	23.8	22.6	21.3	23.2	30	22.3	20.5	25.6	21.2	24.2	22.1

	Mean	20.2	19.7	20	16.8	19.5	20.9	15.6	18.9	18.2	19.6	16.2	21.4	19.3
	Min	17.8	15.2	15.7	13.6	17	19.1	11.5	15.8	13.5	12.5	13	19.8	17
Humidity %	Max	74.8	72	75.5	73.4	69.2	78.5	81.8	75.5	92	79.6	75.9	76.4	78.2
	Mean	50.7	49	50.7	52.3	50.6	55.2	64.9	53	61.6	57.5	54.4	56	52.7
	Min	35.5	36.1	36.8	31.9	37.5	39.5	42.7	37.8	44.2	40.7	35.1	37.2	32.4

Figure 3.10 shows the comfort parameters in the living room and bedroom in the Givoni bioclimatic chart (Givoni 1969). The green color indicates the comfort area in buildings. All of the first-floor apartments are within the comfort zone, with the exception of the bedroom in apartment A2 facing east, which is occupied by one person. On the other hand, two east-facing apartments on the second floor are also located outside the comfort zone next to three apartments on the second floor facing different directions. It was concluded that the ground level and orientation have an impact on the comfort conditions of the apartments. It should be noted that some occupants prefer to use heavy clothes rather than the heating system to minimize energy consumption like the occupant of the apartment A4.

Figure 3.11 illustrates the standard variation of humidity as a function of the standard deviation of temperature in winter for various levels. It shows that the apartment level has low impact on the variation of the temperature and humidity.

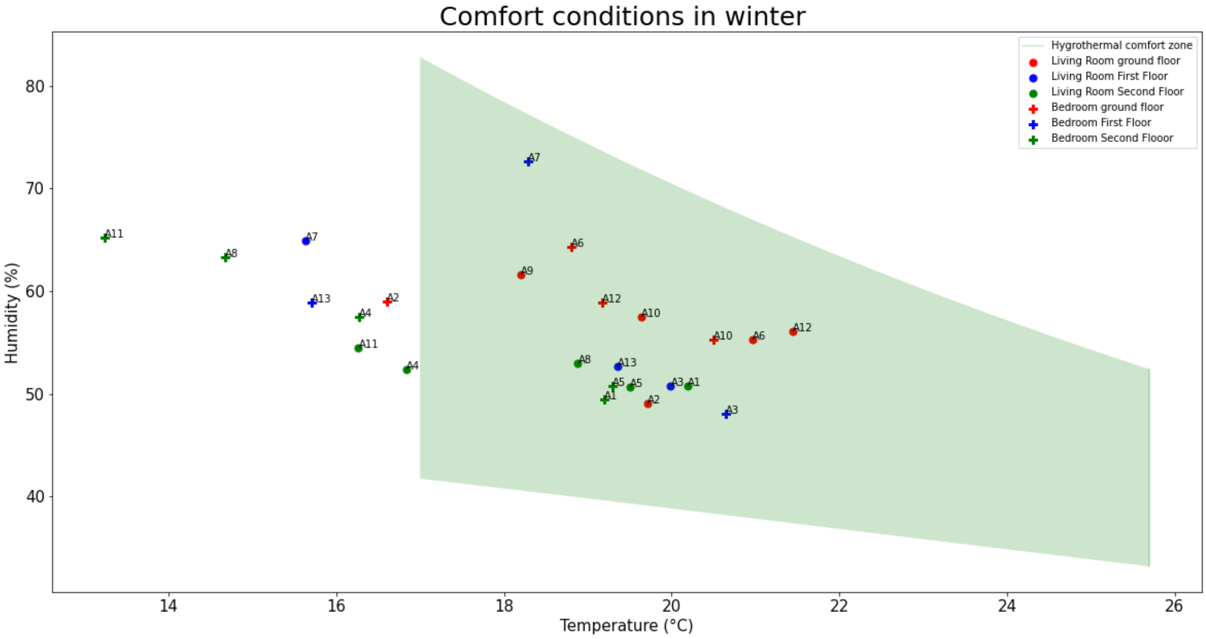

Figure 3.10 Comfort conditions in winter

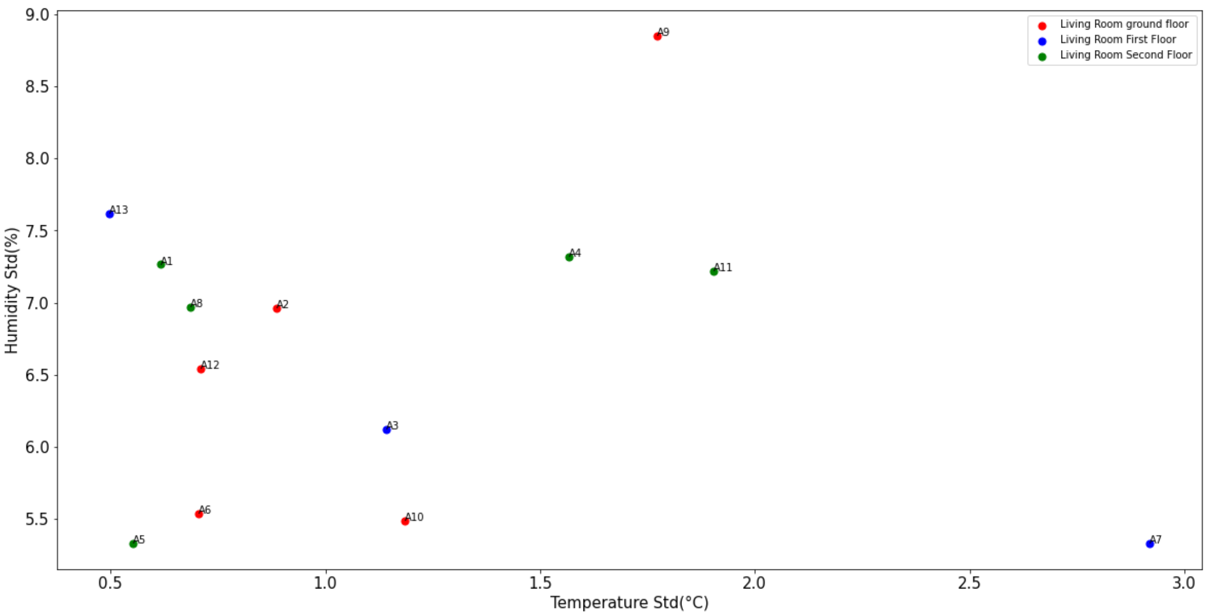

Figure 3.11 Influence of the floor of the apartment on the variation of the humidity according to the variation of the temperature in winter

3.3.1.2 <u>Energy consumption</u>

a) Share in energy consumption

Energy consumption includes the following categories: Heating, hot water equipment and lighting, the hot water equipment includes the ventilation. Figure 3.12 shows repartition of the energy consumption for the totality of the apartments. Energy heating and hot water consumptions account for 70% and 28% of the total energy consumption, respectively. The consumption of the lighting system is negligeable, because it accounts for only 2% of the total energy consumption. In the following the discussion will focus on energy consumption for heating and hot water.

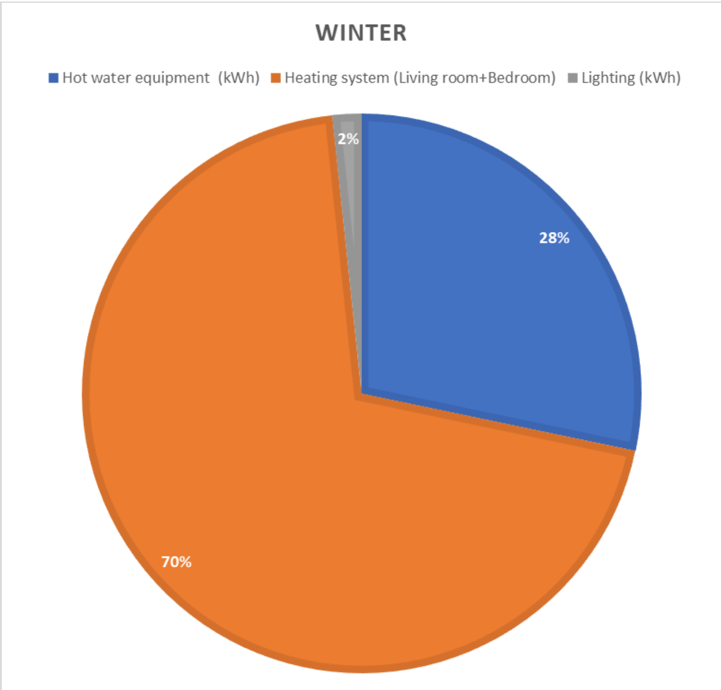

Figure 3.12 Share of energy consumption in winter

b) Heating energy consumption

Figure 3.13 and table 3.4 illustrate the total heating energy consumption in the 11 monitored apartments. The highest energy consumption was recorded by apartment A12, located on the first floor and facing east, occupied by 4 people, followed by the second-floor apartments facing west, occupied by three and two people respectively, while apartment A6, occupied by seven people, consumed less than half its energy consumption. The lowest consumption was recorded by the second-floor apartment A3 due to the non-use of the electric heating system of the apartment and the preference for other heating products for the reason that the new product does not consume much. On average, the heating system consumes 15.83 kWh per m² of energy during the winter season with a standard deviation of 13.87 kWh per m², which indicates that consumption differs greatly from one apartment to another and that the behavior of the occupants has a major role on the consumption of their apartments for example: the occupant of apartment A4 prefers to use clothing insolation to maintain comfort conditions rather than turning on the heat, thus reducing the energy consumption of the heating system.

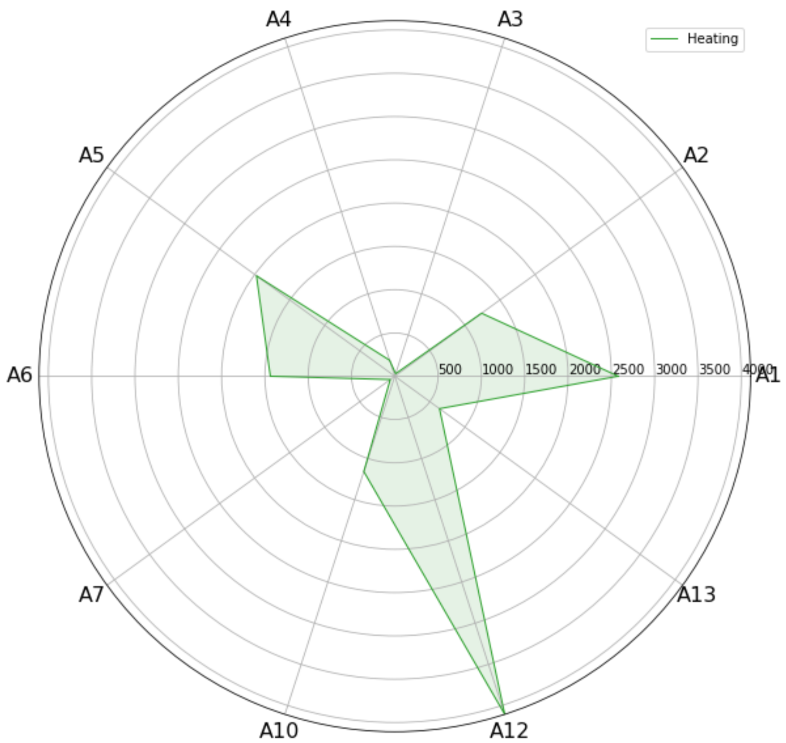

Figure 3.13 Heat energy consumption variation (kWh) in winter

Table 3.4 Heating energy consumption (winter) (kWh)

Apartment	Total (kWh)	Total/m²
A1	2579.5	32.24
A2	1238.3	13.03

A3	30.8	0.47
A4	193.7	4.3
A5	1974.7	24.68
A6	1437.2	15.13
A7	65.6	1.01
A8	--	--
A9	--	--
A10	1157.9	14.47
A11	--	--
A12	4106.1	43.22
A13	637.7	9.81
Average (kWh)	1342.1	15.83
Max (kWh)	4106.1	43.22
Min (kWh)	30.8	0.47
Standard deviation (kWh)	1281.87	13.87

c) Hot water energy consumption

Figure 3.14 shows the total energy consumed by the hot water equipment during the winter, while Table 3.5 shows the total energy statics and the total energy consumption by the occupants. The highest hot water consumption, 1600 kWh, was recorded in apartment A6 occupied by seven people. The north-facing apartments had the lowest hot water consumption (A3 and A4). On average, the hot water tank consumption is 165.64 kWh/occupant in winter (Table 3.5) with a maximum of 414 kWh/occupant recorded in the east-facing apartment A2 occupied by one person and a minimum of 47.8 kWh/occupant recorded in the first-floor apartment A3 occupied by six people, The standard deviation of the hot water consumption indicates a large variation. between occupant profiles, which means that occupants' awareness and habits have a major role on the energy consumption of hot water equipment.

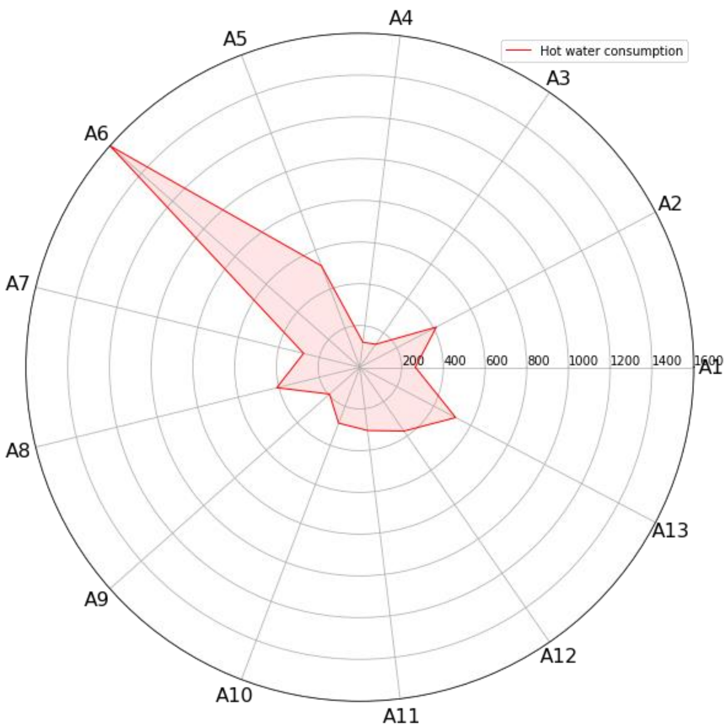

Figure 3.14 Hot water energy consumption (kWh)(Winter)

Table 3.5 Hot water energy consumption

Apartment	Total (kWh)	Total/ occupant
A1	266.1	88.7

A2	414	414
A3	133.9	66.95
A4	120.8	120.8
A5	520	260.8
A6	1600	228.57
A7	277	92.6
A8	410	136.77
A9	194	194.2
A10	286	47.8
A11	305	305.4
A12	371	92.98
A13	519	103.8
Average	416,67	165.64
Max	1600	414
Min	120.8	47.8
Standard deviation	377.75	108.73

d) Hot water consumption

Figure 3.15 and table 3.6 illustrate the total hot water consumption during winter. Ground-floor apartment A6, occupied by seven people, had high hot water consumption followed by east-facing apartment A10 occupied by six people, while apartment A9, occupied only by a disabled man, had the lowest hot water consumption. On average, occupants consume 3233 liters of hot water during the winter season with a maximum of 5546/occupant for an east-facing first floor apartment occupied by one person and a minimum of 745/occupant for a second-floor apartment occupied by five people. Unlike energy consumption, the hot water consumption varies according to the number of occupants.

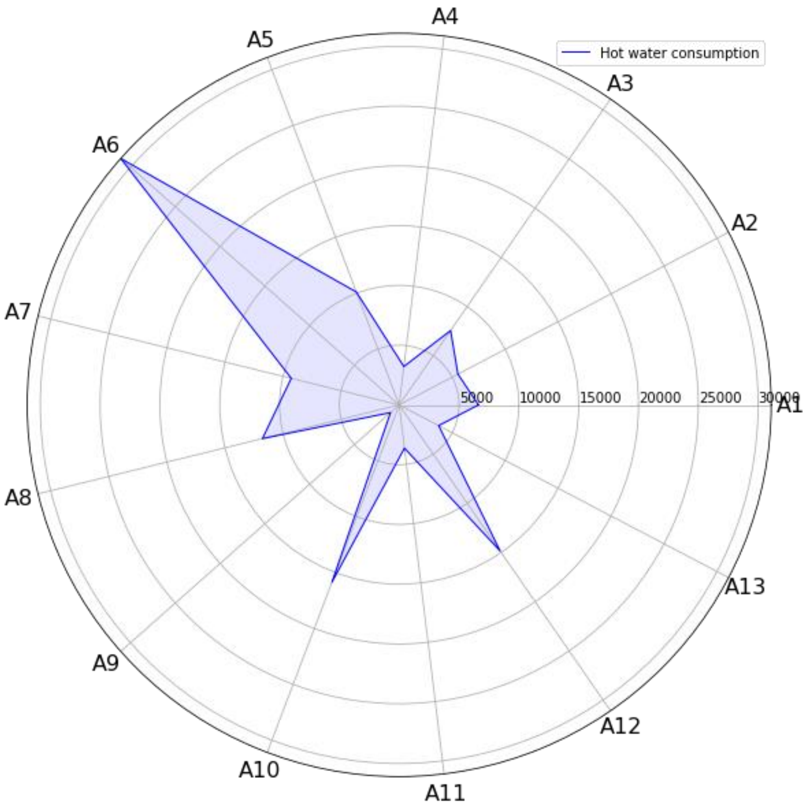

Figure 3.15 Hot water consumption in winter(L)

Table 3.6 Hot water consumption (L)

Apartment	Total	Total/ occupant
A1	6624	2208
A2	5546	5546
A3	7562	3781
A4	3235	3235

A5	10101	5050
A6	31095	4442
A7	9292	3097
A8	11775	3925
A9	968	968
A10	15862	2643
A11	3643	3643
A12	14843	3710
A13	3725	745
Average	9559.3	3233
Max	31095	5546
Min	968	745
Standard deviation	7896.53	1657

Monitoring hot water consumption on a daily basis gives an idea of the consumption status and allows easy detection of overconsumption and water leaks. Figure 3.16 shows the daily hot water consumption per person and the threshold of 45L according to K Tumanova et al (2017), we detect three cases of overconsumption, one of them, apartment A2, turned out to be a case of water leakage after confirmation from the occupant.

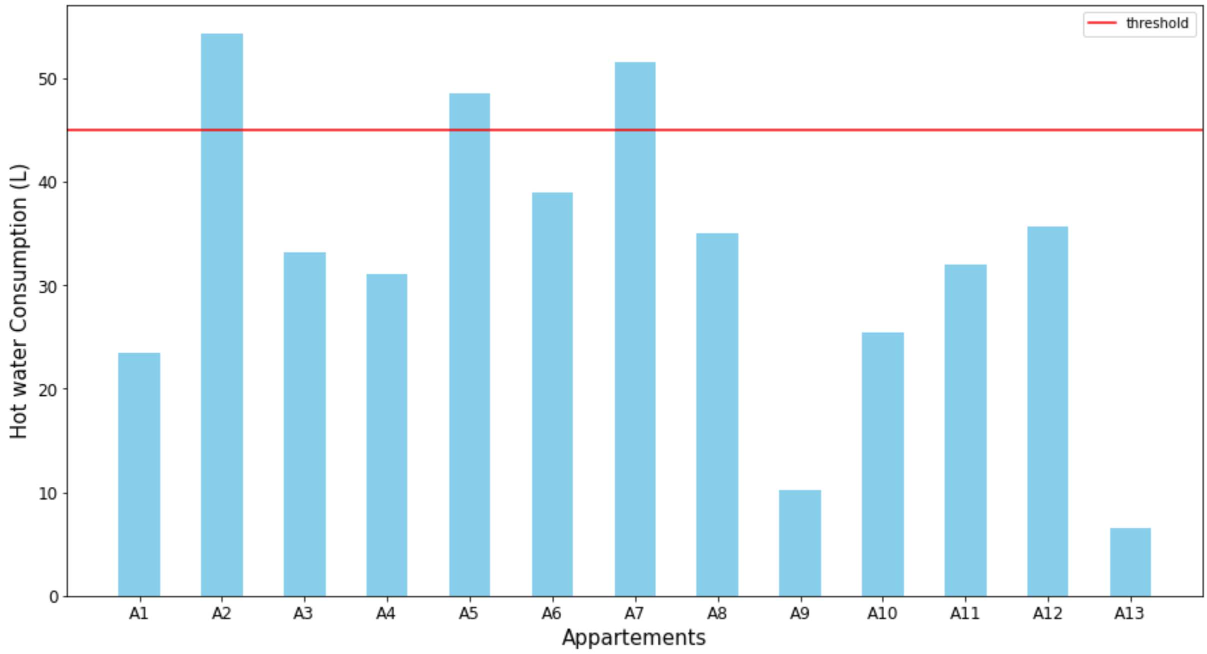

Figure 3.16 Daily hot water consumption per person (L)

e) Relationship hot water consumption and related energy consumption

Figures 3.17 illustrates the relationship between the hot water consumption and related energy consumption. It shows that the hot water equipment consumes on average 0.0409 kWh to heat one liter of water in winter. the non-linearity of the graphs leads us to discover that there is another parameter which is added to the energy consumed by the hot water equipment, this parameter is the energy consumed by the ventilation (VMC) which sometimes consumes more than the consumption of the tank as shown in figure 3.18.

The high consumption of VMC is due to the clogging rate and the maintenance of the filter, for example we found a clogging rate of 94% in apartment A11 while it is only 4% in apartment A4. In addition, the hot water tank configuration plays an important role in energy savings. We found that occupants using the manual mode save more energy, such as apartments A3 and A4, than the automatic mode.

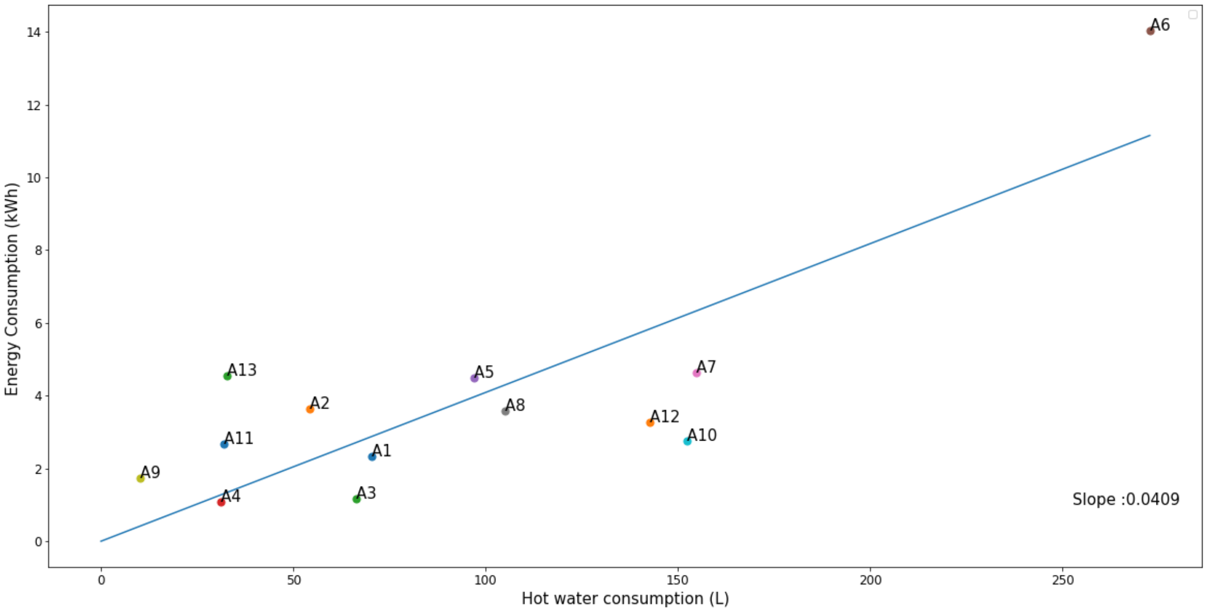

Figure 3.17 Relationship between hot water consumption and related energy consumption

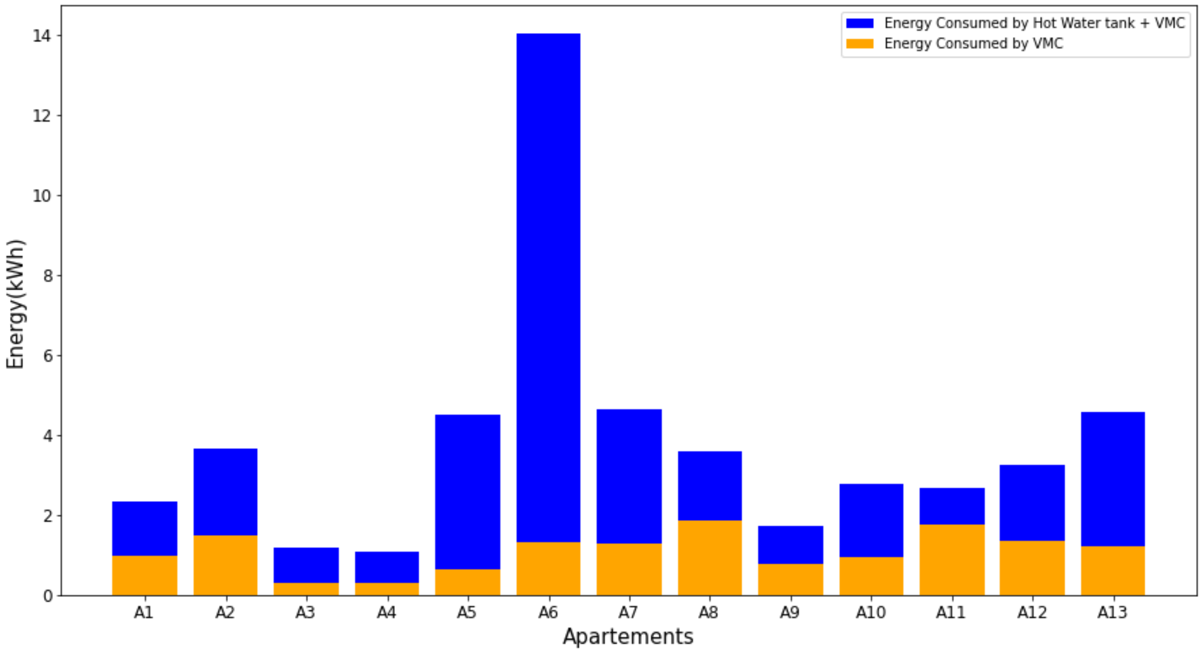

Figure 3.18 Daily Hot water tank and VMC consumption in winter (kWh)

The energy consumed by the VMC can be reduced by cleaning and maintaining the filter. Figure 3.19 shows the annual savings in euros that can be achieved if we reduce the energy consumed by the VMC which can reach 100 euros/year.

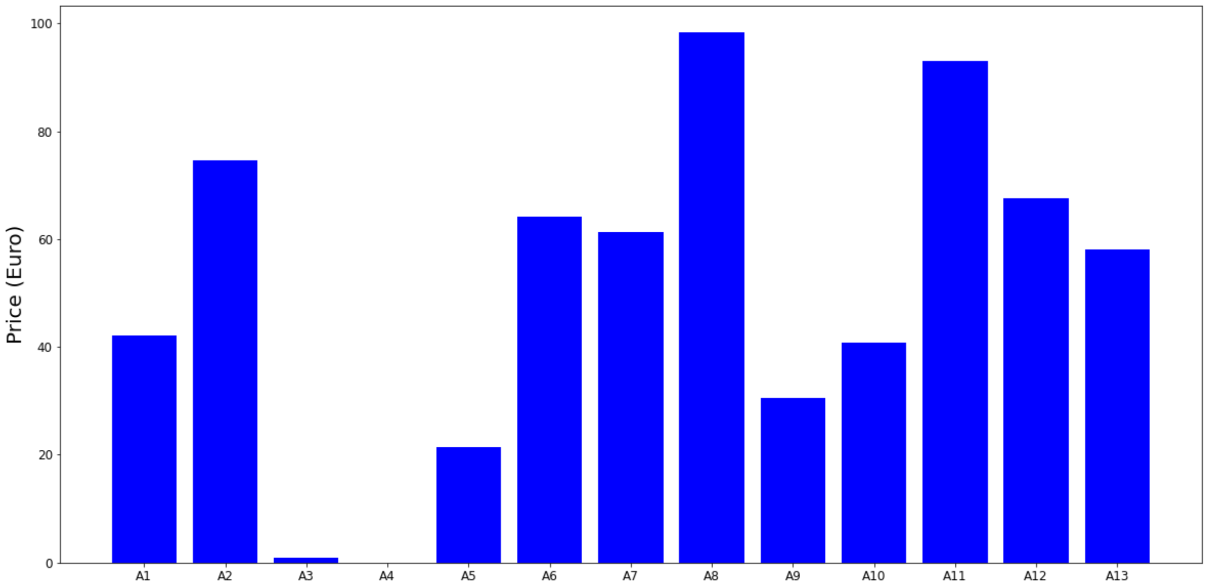

Figure 3.19 Annual savings for the VMC (Euros)

3.3.2 Summer Saison

3.3.2.1 Comfort Conditions

Figures 3.20 and 3.21 illustrate the variation of humidity and temperature in apartment A6 during the summer season. The indoor temperature varied between 19.6°C and 29.6°C and the humidity varied between 31.9°C and 77.9°C. The variation of temperature and humidity in the bedroom and living room follows the same curve with a small difference that varies over time.

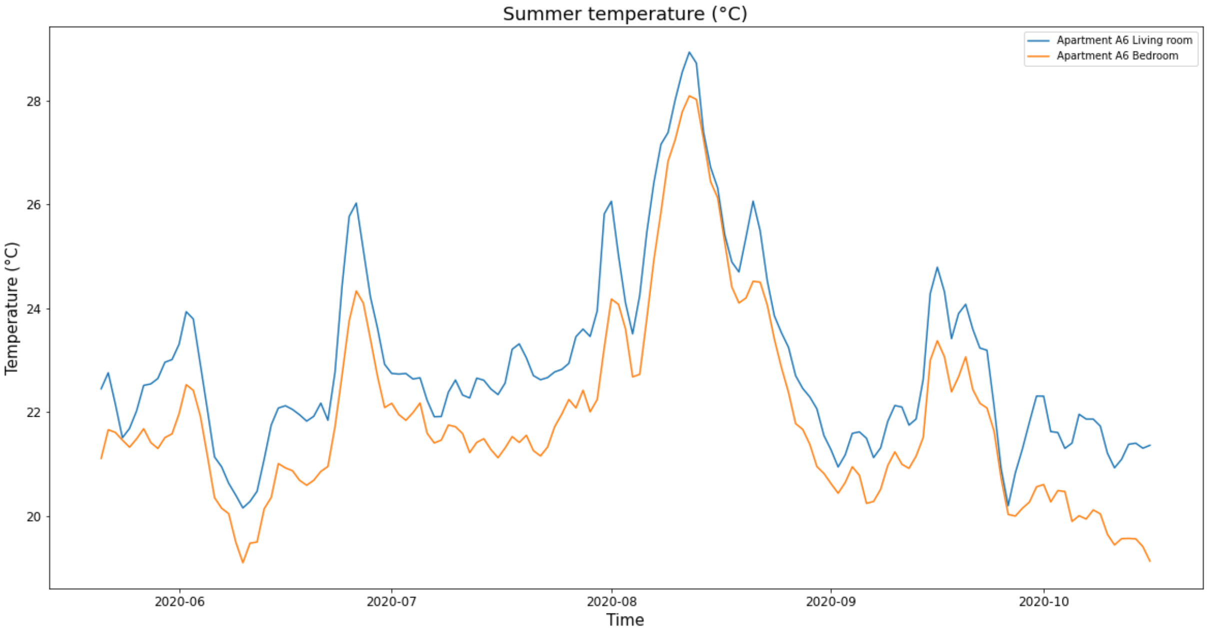

Figure 3.20 Variation of the temperature in Summer

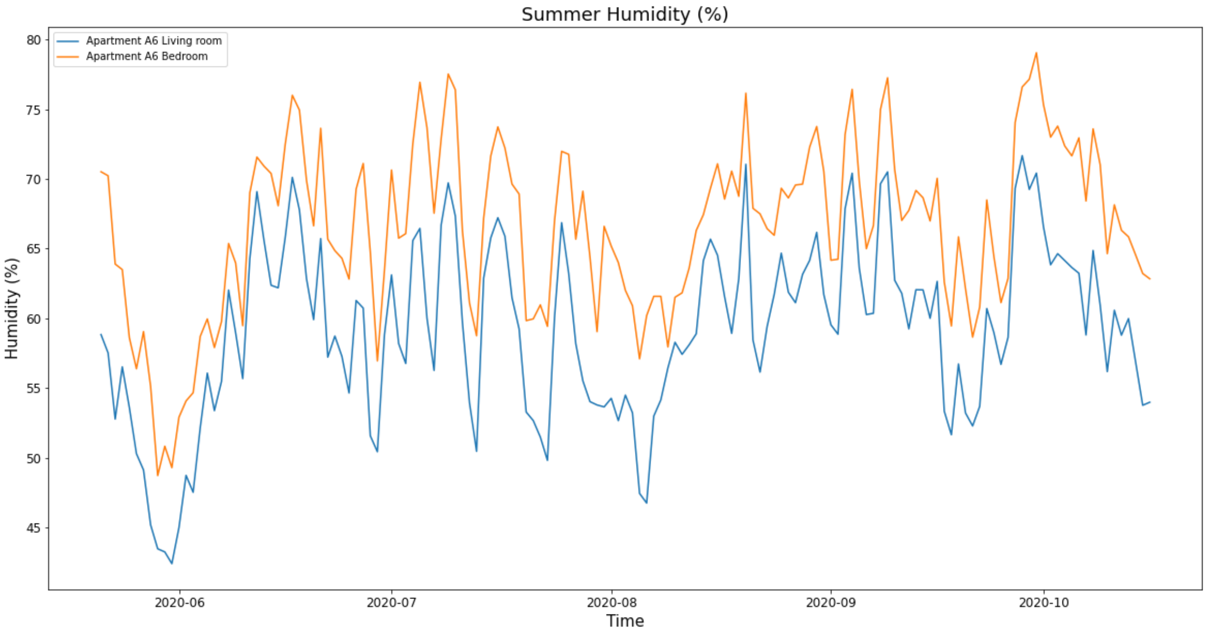

Figure 3.21 Variation of the Humidity in Summer

Figure 3.22 shows the comfort parameters in the living room and bedroom in the Givoni bioclimatic chart. Almost all apartments are in the summer comfort zone, except for three first floor apartments, two facing east and one facing west. It can be seen that the second-floor apartments have low humidity values, followed by the first-floor apartments, indicating that the floor level of the apartments has an influence on the comfort conditions of the apartments. Moreover, Data shows that the floor of the apartments greatly influences the temperature variation during summer as shown in Figure 3.23. The apartments in the second floor tend to have a large variation in temperature, unlike the apartments located in the first floor.

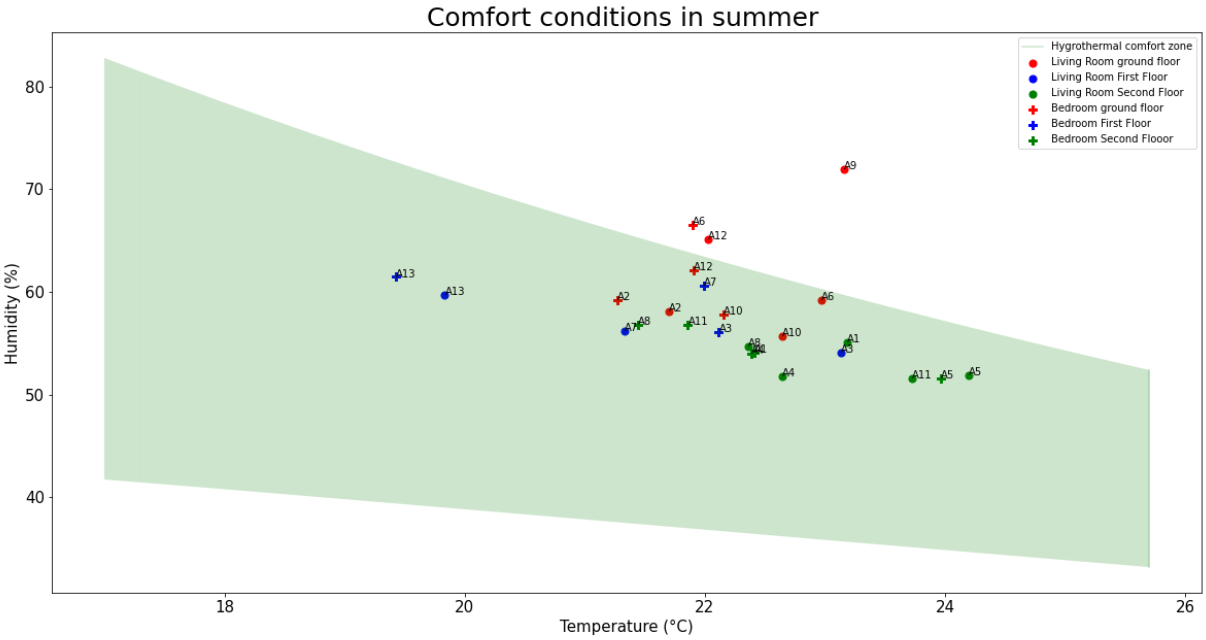

Figure 3.22 Comfort conditions in summer

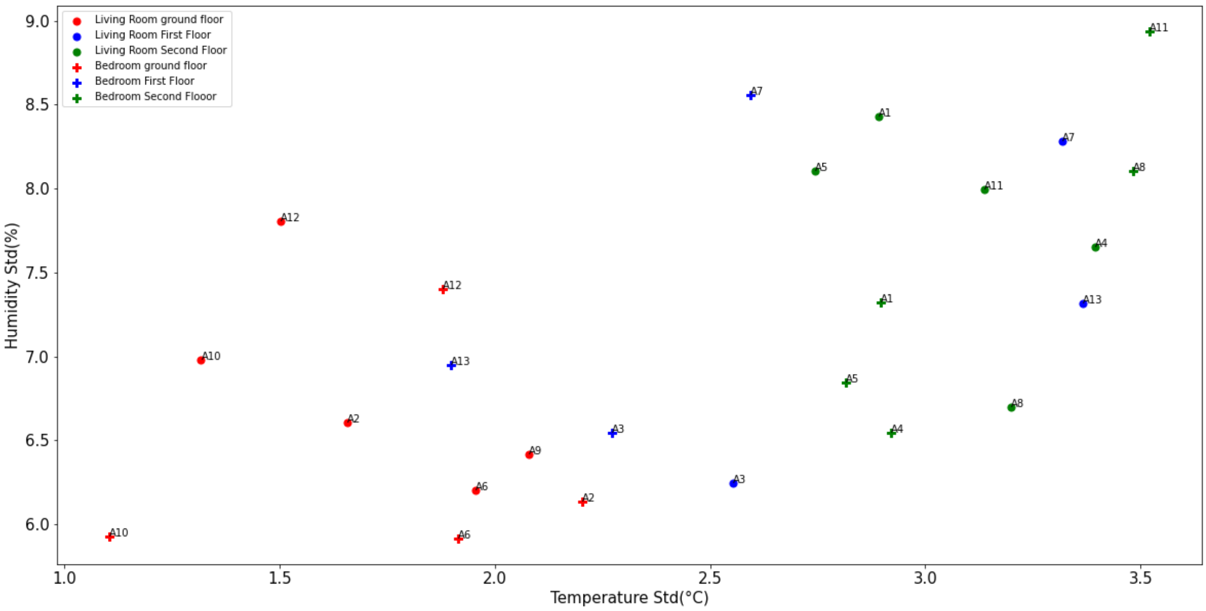

Figure 3.23 Average values of temperature and humidity on the apartments (Summer)

3.3.2.2 Energy consumption

a) Share in energy consumption

Figure 3.24 shows the share in energy consumption during the summer season. The hot water tank is responsible for 80% of the energy consumption in summer while the heating system represents only 15% of the energy consumption to be compared with the share in energy consumption in Winter: 28% for the hot water and 70% for heating.

Table 3.7 clearly shows that all energy consumptions increase significantly in winter, at different rates. The heating system increases by 1555%, while the hot water tank consumption increases by 29.7%, which probably means that the occupants do not change their showering and hot water use habits much during the winter season. Overall, the total energy consumption doubled compared to the summer season.

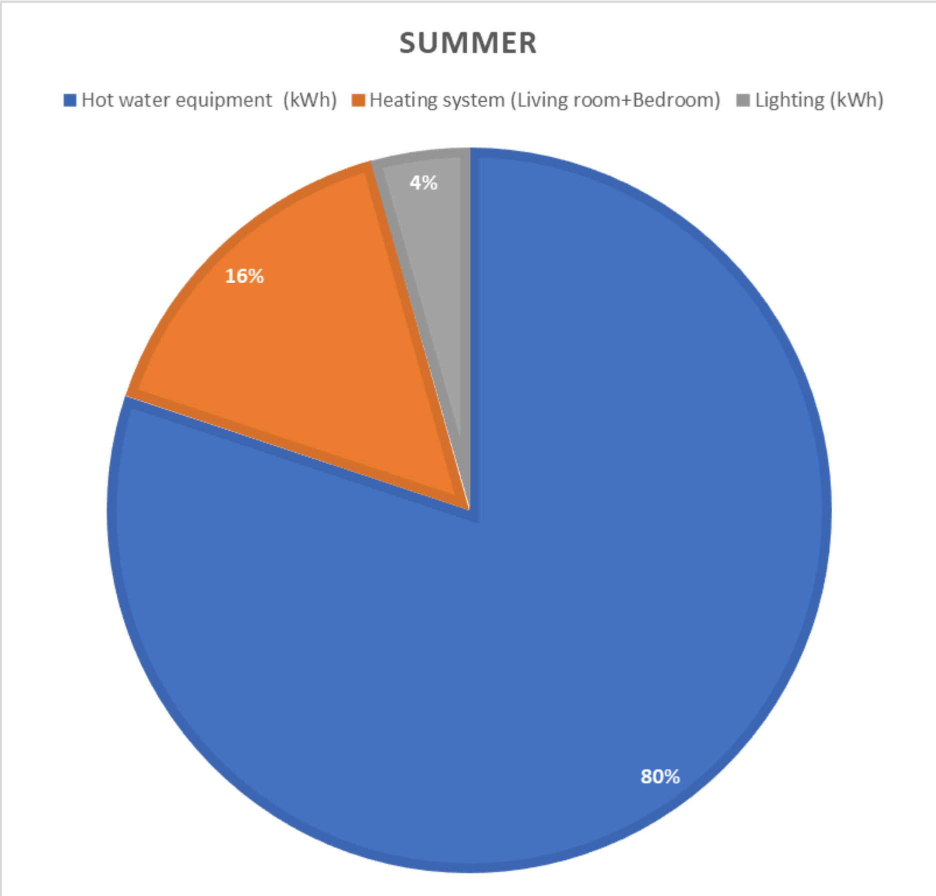

Figure 3.24 Share of energy consumption in summer season

Table 3.7 Total energy consumption in summer and winter season

Energy consumption	Summer	Winter	Variation (%)
Hot water tank (kWh)	4180,4	5420,3	29,7
Heating system (Living room+Bedroom)	810,6	13421,5	1555,7
Lighting (kWh)	227,6	320,6	40,9
Total (kWh)	5218,6	19162,4	267,2

b) Hot water energy consumption

Figure 3.25 shows the total energy consumption of the hot water equipment. The occupants' consumption profiles has low impact on hot water energy consumption, comparer to Winter.

The highest energy consumption was recorded by the east-facing first floor apartment A6, occupied by six people, followed by the west-facing second floor apartment with two occupants, as shown in Figure 3.25. The lowest consumption was recorded by the north-facing apartment A4 on the second floor. As explained earlier, hot water energy consumption is influenced by occupant habits and awareness, as well as maintenance and hot water equipment settings such as manual and automatic modes.

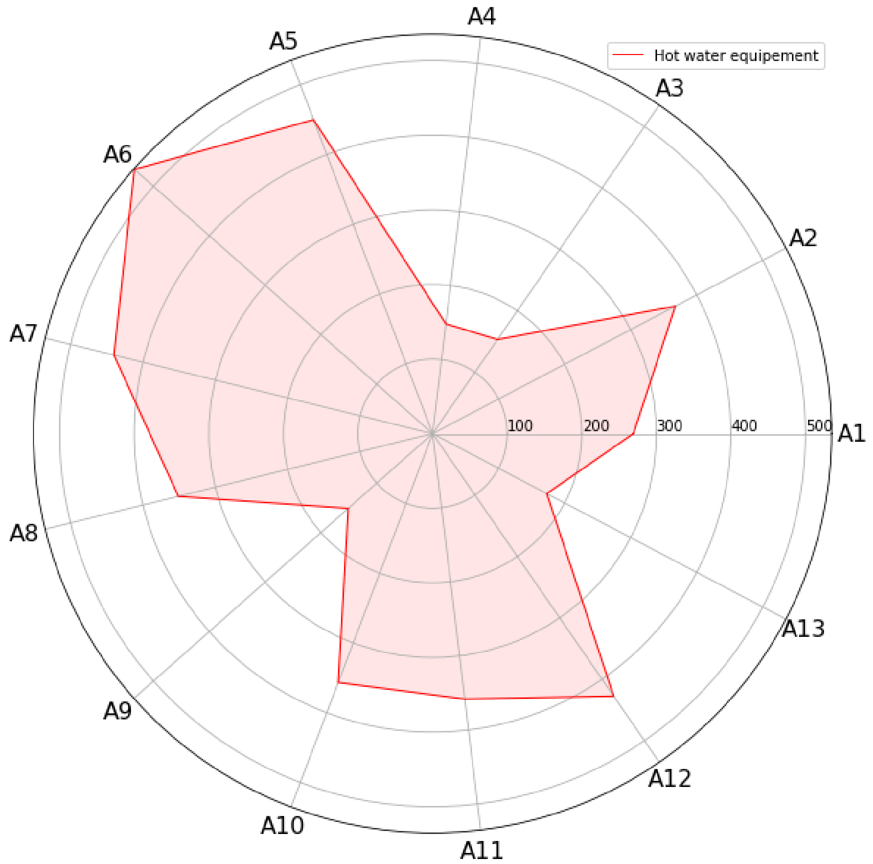

Figure 3.25 Total hot water energy consumption in summer (kWh)

c) Hot water consumption

Figure 3.26 shows the hot water consumption in summer. The first-floor apartments occupied by 7 and 6 people, respectively, show the highest hot water consumption, while a first-floor apartment occupied by a single occupant shows the lowest consumption. This result confirms that the apartments with the highest occupations have the highest hot water consumption.

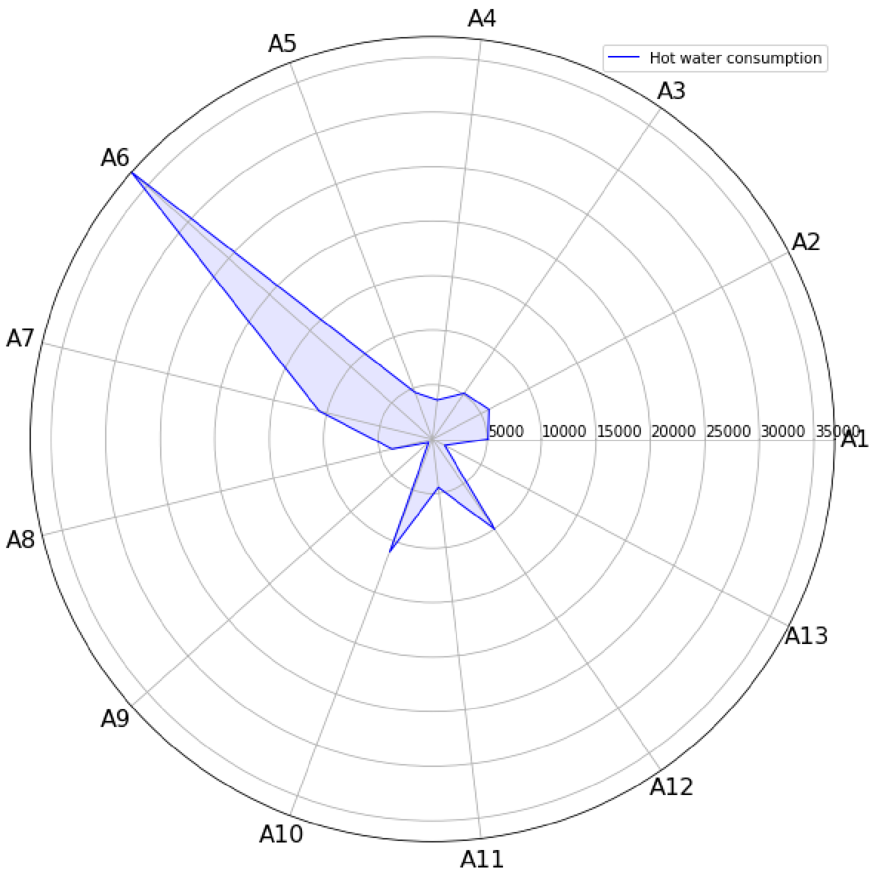

Figure 3.26 Total hot water consumption in summer (L)

e) Relationship hot water consumption and related energy consumption

On average, 0.034 kWh are used to heat one liter of water during the summer season as shown in Figure 3.27, in contrast to the winter season which requires more energy for heating. It should be mentioned that the no-linearity between the hot water consumption and the energy consumption of the hot water tank are caused by the consumption of the VMC as mentioned earlier in the winter results.

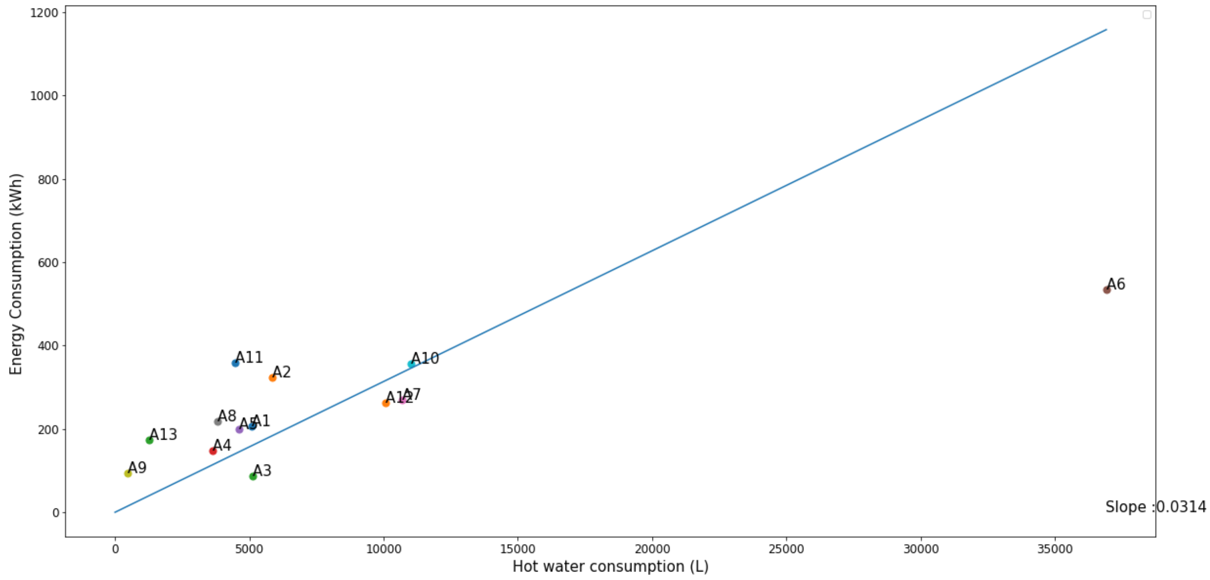

Figure 3.27 hot water consumption according to the consumption of the hot water equipment in summer

Figure 3.28 shows the energy consumption of the hot water tank and the VMC, the latter represents an important percentage of the energy consumption in some apartments which is a lost energy due to the lack of maintenance of the filter.

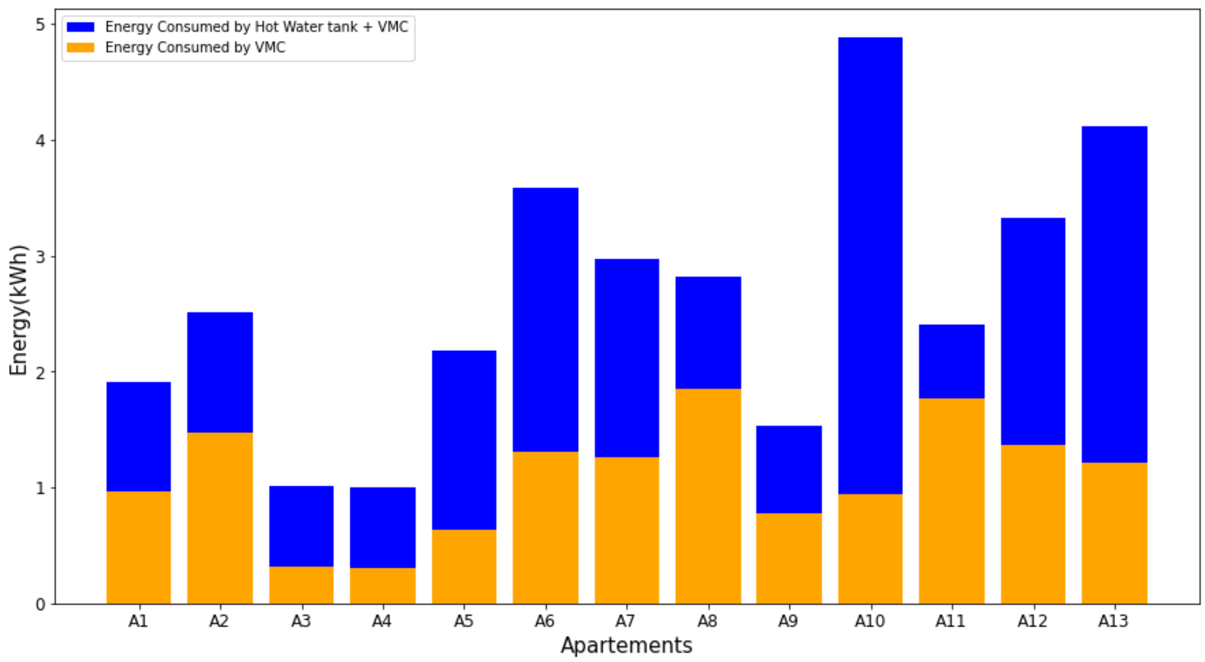

Figure 3.28 Daily Hot water tank and VMC consumption in summer

3.4 Conclusion:

This chapter presents an investigation of the comfort conditions and energy and hot water consumption in 13 social housing apartments houses located in the north of France. The apartments were monitored with a smart system that record the comfort conditions, hot water consumption and energy consumed for heating, hot water and lighting.

The results show that the majority of apartments are in the comfort zone during the summer season. In winter some apartments are outside the comfort zone because of the will of some occupants to under heat their appartement to save energy expanses.

The total energy consumption in winter is double that of summer.

Occupants' awareness and willingness play an important role in reducing the consumption of appliances that can be controlled such as lighting and heating, for example building A12 and A1 use energy saving bulbs to reduce lighting consumption, and building A9 follows a strict strategy of turning on only the necessary bulbs and never leaving appliances in standby mode, thus saving energy.

The monitoring system allows occupants to track their energy consumption and comfort conditions. The system allowed to detect a water leak in one apartment and excessive energy consumption in some buildings. Results showed the necessity of the maintenance of the ventilation to avoid energy waste.

General Conclusion

This research aimed at developing an effective smart system that can help implement smart building technology in various types of buildings. It also aimed to investigate the smart building services in two types of buildings: Higher education classrooms and social housing. The primary service for the former (classrooms) concerns the quality of the indoor conditions and their impact on the learning capacity of students. The services for the social housing concern the indoor comfort quality, including temperature and humidity and energy efficiency with a focus on both occupants' behavior and technical equipment.

The research followed a pragmatic scientific approach which combines the identification of significant challenges, the development of a robust monitoring system, data collection from both sensors and users, and data analysis to explore the significant behavior trends, detect operating anomalies, and establishing a set of recommendation to improve the efficiency of systems under concern.

The significant outcome of this research could be summarized as follows.

1) Comprehensive monitoring system for smart buildings

The comprehensive monitoring system which was developed for smart buildings has proved to be effective. It could be easily installed in various operating conditions. It also allows monitoring the indoor comfort, air quality, fluid consumption, and building safety. Moreover, the system could be extended easily to host new components and services. The hardware and software components were selected or developed to ensure high performance in low energy consumption, rapid data collection, and treatment. This system was well described in this manuscript.

Consequently, it could be easily reproduced by scholars and professionals. ***For instance, this system allows data collection from sensors. In the future, it could be extended to collect data from users using mobile applications.***

2) Impact of classroom indoor conditions on students learning capacity

The research on the impact of the indoor classroom environment on students' learning efficiency was based on monitoring the classroom comfort parameters and a questionnaire about the students' feedback and assessment of comfort conditions and learning effectiveness.

Results showed significant spatial variation in indoor comfort conditions, especially for the temperature and CO2 concentration. This research resulted in some recommendations, such as installing a ventilation system in the classroom to reduce the magnitude of variation in the comfort conditions and regularly open the classroom windows.

For instance, this research was conducted in small classrooms. In the future, it should be extended to large classrooms and the use of mobile applications to collect the students' feedback.

3) Comfort and energy efficiency in social housing

The monitoring system was used to track the indoor comfort conditions and energy consumption in 13 occupied social housing apartments.

Results showed that almost all the instrumented apartments were within the comfort zone in summer. But in Winter, some apartments were underheated because of the difficulties of some occupants to afford energy expenses. The research also showed that the occupants' awareness plays an essential role in energy savings.

This research was limited to a simplified analysis of collected data. In the future, the extension of the monitoring program to a high number of buildings requires the development of robust data analysis tools based on Machine Learning.

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