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Development of a system to assess the use of energy flexibility in office buildings

Dissertação para obtenção do Grau de Mestre em Engenharia Eletrotécnica e de computadores

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Caracterização e gestão dos consumos de eletricidade de um espaço laboratorial - abordagem baseada no paradigma "Living Lab"

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Resumo

Esta dissertação apresenta um sistema que permite desenvolver e avaliar remotamente metodologias que utilizam a flexibilidade energética disponibilizada por dispositivos controláveis presentes em edifícios de escritórios. Tendo em conta a importância do conforto dos ocupantes no estudo da flexibilidade energética, o sistema foi desenvolvido considerando um contexto *Living Lab*, onde os ocupantes dos edifícios têm uma participação ativa na caracterização e utilização da referida flexibilidade. Para ilustrar o funcionamento do sistema desenvolvido considerou-se um caso de estudo onde a flexibilidade energética é fornecida por uma bomba de calor, sendo o seu funcionamento controlado com o objetivo de reduzir os custos associados ao consumo de energia elétrica do escritório em questão. Os resultados obtidos mostram que a utilização da flexibilidade energética pode conduzir a poupanças, que resultam de um menor consumo energético nos períodos associados a tarifas mais elevadas, enquanto os níveis de conforto térmico dos ocupantes são respeitados.

Palavras-chave: Demand Response, Living Lab, Flexibilidade Energética, Internet of Things.

Abstract

This dissertation presents a system that allows the remote development and evaluation of methodologies that use the energy flexibility provided by controllable devices present in office buildings. Considering the importance of occupant comfort in the study of energy flexibility, the system was developed considering a Living Lab context, where building occupants have an active participation in the characterization and use of such flexibility. To illustrate the operation of the developed system, it was considered a case study where the energy flexibility is provided by a heat pump, being its operation controlled with the objective of reducing the costs associated with the office electricity consumption. The results show that the use of energy flexibility can lead to savings resulting from lower energy consumption during periods associated with higher tariffs, while occupant thermal comfort levels are respected.

Keywords: Demand Response, Living Lab, Energy Flexibility, Internet of Things.

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Acronyms

IOT Internet of Things

DR Demand Response

AC Air Conditioning

RCU Remote Control Unit

BEMS Building Energy Management Systems

ICT Information and Communication Technologies

HEMS Home Energy Management Systems

PSS Product Service Systems

RFIDs Radio Frequency Identification Systems

TOU Time-of-Use

1 Introduction

In this chapter, the background and motivation for this research work are presented in Section 1.1. The objectives to be achieved are described in Section 1.2, while the structure of the document is presented in Section 1.3.

1.1 Motivation

Of all the problems humanity will face in the future, some consider energy one of the biggest and most difficult challenge of all [1]. Energy is consumed in large quantities and, according to World International Outlook 2018 [2], world energy consumption will grow by almost 90% between 2018 and 2040. Among other factors, this is also due to overpopulation together with growing industrialization and rising living standards in developing countries. For instance, according to the Population Reference Bureau (2018) *"the world population will reach 9.9 billion by 2050, up 2.3 billion or 29 percent from an estimated 7.6 billion people now"* [3].

Every day the effects of global warming can be witnessed through various multimedia outputs; the melting of the arctic, the animals losing their habitat and being threatened with extinction and the increasing extreme weather conditions in the world [4]. In the summer of 2019, Europe experienced unusually high temperatures, while in the United States there is a growing number of tornadoes, floods and extreme heat [5]. These extreme weather occurrences and landscape changes are being pointed out as associated to global warming, of which one contributor may be the use of fossil fuels [6].

Fossil fuels have a huge impact on the health of our planet, increasing the levels of greenhouse gases in the atmosphere, leading to climate change and bringing adverse effects on humanity, habitat and our quality of life [3]. However, people are now more aware of the effects of greenhouse gas emissions, which has motivated the search for new and more sustainable energy solutions.

There has been an increase in renewable energy sources in the grid to meet the long-term climate and sustainability goals and, in some cases, also motivated by other factors (e.g. costs). Renewable energy sources vary over a season or even a day and can increase pressure on power systems. In addition, the use of renewable energy sources is limited because renewable energy sources do not always meet grid needs and can only be stored a limited amount [7]. Due to the uncertainty of availability of renewable energy sources, in combination with other factors (e.g. economical), most countries prefer to keep other reliable sources of energy, such as nuclear, gas and coal in reserve in case variable energy sources fail [2]. Hence the need for smarter solutions with improvements in efficiency and use of demand flexibility to support grid operation.

The electric grid is the network through which power is generated, transmitted and distributed to customers, solving, therefore, the problem of geographic separation between electricity production and consumption. The development of power grids allows various producers to share the same infrastructure for production and distribution, which increases reliability and lowers costs. However, with the increasing demand for energy comes the need for more efficient systems to reduce energy consumption and/or to adapt consumption according to power grids needs using the available energy flexibility.

In developed countries, of total final energy consumption, buildings account for 20-40% [8]. As they represent a significant part of total final energy consumption, it is important to seek to reduce energy consumption in buildings and use the available energy flexibility. New enablers of flexible electrical systems, such as Internet of Things, Demand response methods and Living labs, help change the service offered, allowing to make smarter choices and reduce or increase energy demand during certain periods. Flexibility is the ability to modify something. Energy flexibility can be used to adapt energy consumption according to certain objectives and can then be applied to improve the operation of power grids through the implementation of Demand response (DR) methods.

As building’s occupants can have a key role in the use of flexible systems, Living Labs can be used to develop and assess methodologies that use such flexibility to apply DR strategies, while considering the comfort needs of the occupants. Living Labs can be used to improve e.g. energy management, photovoltaic self-consumption or to reduce electricity costs by being a vehicle to test new strategies. The importance of testing new technologies, aligned with the participation and access of users, is therefore relevant in this time and age.

1.2 Objectives

The study focuses on energy flexibility available in office buildings, that accounts for 20-40% of total energy consumption, due to its relevance. In office environments, users interact and adjust the settings to maintain user comfort levels. Aims to control indoor office loads such as heating and cooling since lighting and outlet power are typically required most of the time. These settings can be made to react to office conditions automatically and act according to the user requirements with the help of smart systems.

One of the objectives of this research is to study a remote Living Lab where the user (building occupant) is the key element controlling the remote control unit. Living Labs can have the benefit of offering resource sharing allowing others to research on the implemented Living Lab. However, as will be seen in the literature review, there is a lack of research on remote Living Labs which would allow remote access to researchers who do not have physical access to the Living Lab. To achieve a remote Living Lab, a system will be developed with a divided architecture so that the Living Lab is independent from the remote control unit, where the methodologies are developed to use the available energy flexibility. In addition, the Living Lab will be based on a modular architecture in which each component of the system can be implemented and replaced according to existing technologies.

There is a growing interest in the Internet of Things (IoT) and its application in various aspects of human activity, including manufacturing, intelligent buildings, care for the elderly, etc. This work intends to follow this trend, especially within the context of the remote Living Lab. Given an office building physical space, this work includes an Interface that allows the remote monitoring of various parameters associated with the Living Lab conditions, as well as the control of some devices located in the Living Lab.

To summarize, this study will develop a solution for monitoring and controlling the temperature conditions of a Living Lab using energy flexibility provided by a heat pump by applying DR methods on a remote control unit. Considering a specific case study, this work will also seek to answer the question: does using the energy flexibility provided by a heat pump in an office environment using demand response methods result in cost savings?

1.3 Structure

The motivation and objectives for this work have been presented in Section 1.1 and 1.2, respectively. In addition to the first chapter where the introduction is presented, this document contains four more chapters which are described below.

Chapter 2 – Literature Review and Background Information

This chapter introduces the concepts of Living Lab, Internet of Things, and energy flexibility. Additionally, a discussion is elaborated on the possible approaches and methods for the use of the energy flexibility provided by controllable devices in office buildings.

Chapter 3 – Flex lab

This chapter introduces the conceptual model and architecture used in order to make possible the implementation of the proposed platform, as well as the benefits and features available for the user. It also presents a description of the technologies used in the implementation as well as the detail of the physical and virtual levels of the platform.

Chapter 4 - Results and Analysis

This chapter presents the case study and the different scenarios considered to answer the question identified in Section 1.2. The collected results are also presented and analyzed in this chapter.

Chapter 5 - Conclusion and Future Work

This chapter presents a general synthesis of the dissertation, its conclusions and possible future work.

2 Literature Review and Background Information

As was shown in the previous chapter, in order to meet the requirements of a sustainable development, flexible solutions must be studied and adopted. The increase of renewable energy sources and need to electrify everything, creates changes in energy systems which bring new challenges, such as the uncertainty of energy supply, exhaustion of grid operations and more complicated control problems. With this in mind, with the help of users and consideration for their comfort, the Living Lab approach comes as a research strategy for further improvements on the above mentioned challenges. In this chapter the literature review and background information available on the subject will be presented. Energy flexibility will be explained and classified in section 2.1 with the help of table 1, where energy flexibility is quantified by different authors. In section 2.2 is defined a Living Lab and in table 2 a list of Living Labs that focus on energy research and are set on office buildings. A comparison between these studies will also take place in this chapter. In section 2.3 the definition of Internet of Things will be presented as well as its importance to this project as it is going to be the main tool to make the Living Lab remote.

2.1 Energy flexibility

Energy flexibility and, therefore, flexible energy systems, deviate from traditional behavior and are a research strategy for further improvements in network demands [10]. To divert the electricity consumption of a specific building from its normal behavior, there are two most commonly used approaches [11], to anticipate energy consumption of an electrical device or to change the electricity demand to a different period of time. To anticipate energy consumption, one commonly approach is the storage of thermal energy. To change the electricity demand, a frequently used method is the change of operation of devices.

Since Energy flexibility is a new concept, there is no international consensus on how to describe or quantify it. For this reason, a number of different definitions of energy flexible buildings are being drawn in parallel. Although there are different definitions, they all share the same basic idea of energy flexibility being the capability of a building to change, adapt or shift its energy consumption profile[10].

In table 1 some methodologies to quantify energy flexibility of buildings will be shown. Six et al. [12] and Thomas Nuytten [13], define the concept of energy flexibility being quantified in temporal flexibility. In other words, the number of hours the electricity consumption can be delayed or anticipated. Their work is focused on the energy flexibility of residential heat pumps joined with thermal energy storage and the energy flexibility of CHP system. The methodology proposed by De Coninck and L. Helsen [10]-[11], quantified Energy Flexibility by cost functions of the price of electricity. This upholds the possibility of diverting an amount of energy at a specific point or span in time, from the reference scenario with associated costs. This methodology was tested on heating systems that use buildings thermal mass. Olderwurtel et al. [14], used the same case study as De Coninck and L. Helsen [15], but quantified the flexibility through efficiency curves, depicting the maximum and minimum displacement of the power versus the power shifting efficiency. In the scope of this study, it is also relevant to see the D'Hulst et al. [16] research, which quantified flexibility by the power increases or decreases combined with the time the changes could be maintained. The LINEAR project introduced demand response technologies at the residential level and, based on measured data, quantified the flexibility offered by the five different types of household electrical devices.

Most of the studies mentioned below consist of case studies on residential buildings. However, there is a lack of uniformity in definitions to define office buildings and their quantifications of energy flexibility. Hence the need for research regarding energy flexibility quantifications in office buildings.

Table 1 - Energy Flexibility quantifications by different authors

Authors	**Quantification**	**Case Study**
Six et al. [8] Nuyt-ten et al. [9]	Flexibility quantified by the hours the electricity consumption can be shifted forward or backwards in time.	A case study on a residential building, focusing on the flexibility potential of heat pumps combined with thermal energy storage. The other, 100 residential buildings in Belgium, focusing on combined heat and power systems with thermal energy storage.
D'Hulst et al. [16]	Flexibility quantified by power changes combined with the period of time these changes could be maintained.	A case study on residential buildings in Belgium, focusing on different types of domestic electrical devices.
Stinner et al.[17]	Flexibility quantified by flexibility in time, power and energy.	A case study on the building sector focusing on heating systems with thermal storage tanks that are used for space heating and domestic hot water.
De Coninck and L. Helsen [11][18]	Flexibility quantified by the extent of available energy changed at a specific time and the related cost when compared to a reference	A case study on an office building in Belgium, focusing on heating systems that use buildings' thermal mass.
Olderwurtel et al. [10]	Flexibility quantified through efficiency curves, depicting the maximum and minimum displacement of the power versus the power shifting efficiency	A case study on an office building in Switzerland, focusing on heating systems that use buildings' thermal mass.
Reynders et al.[19]	Flexibility quantified by the available storage capacity, the storage efficiency, the power shifting capability and state of charge	A case study on residential buildings in the climate of Belgium, focusing on heating systems that use buildings' thermal mass.

2.2 Living Labs

As was shown with the definition of energy flexibility, there is also a limited amount of literature and a lack of a widely recognized definition of Living Laboratories. Dell'Era and Landoni [12] have come up with a wider definition of a Living Lab, that gathers two main shared concepts, in particular the user-centric approach and the laboratory experimentation environment.

‘A Living Lab is a design research methodology aimed at co-creating innovation through the involvement of aware users in a real-life setting.'

The literature research is going to be restricted to a selection of Living Labs with studies focused on energy and that are confined to an office building setting. Six studies that illustrate studies focused on energy and confined to an office setting, are shown in the table 2.

Table 2 - List of Living Labs

Name	*Monitoring*	*Control*	*Type of Building*	*LL Definition* [20]*	*Summary*
OU44 Building	X	X	Public Building -School	*'Living Labs with the purpose of researching, developing and evaluating real-life scenarios'*	The aim of the study is to improve energy efficiency of public buildings by enabling monitorization, management and control of operations. For this propose, the building uses energy efficient technologies such as ventilation units with heat recovery, LED lights, underfloor heating, PV modules, heating, lightning and electricity consumption sub-meters, and temperature, humidity, CO_2, LUX and PIR sensors on the room level. In Denmark, there is a performance certification tool for buildings, BE10, which gives a static energy performance prediction but does not consider occupancy behavior and weather conditions. It was used a dynamic holistic energy model (Energy Plus) to make a more precise evaluation. This model considers orientation and geometry, energy systems, building services, thermal envelope, constructions, occupancy behavior and weather conditions. The conclusion was that the Energy Plus model allowed a better prediction of the building performance. The average energy performance gap between the BE10 vs actual meters data is 55%, while the Energy Plus model gap reduced to only 11%.
FZI House of Living Labs / Living Lab SmartEnergy	X	X	Private households and commercial buildings	-	The Living Lab Smart Energy investigates solutions for the future energy system. Hence, the labs are equipped with automation, distributed generation, thermal and electrical storage and technologies that enable more flexibility over energy supply and demand. A large number of different devices and building automation technologies provide a suitable research platform for various aspects such as standardized integration, interoperability, smart grid features and power management methods. Based on this platform, optimization strategies are developed to address different energy management goals, such as grid support, economic profit or self-consumption.

Name	Monitoring	Control	Type of Building	LL Definition [20]*	Summary
Longitudinal Living Lab Study of a HEMS	X		Seven households	*'A user-centric research methodology for sensing, prototyping, validating and refining complex solutions in multiple and evolving real life contexts'* - Eriksson et al. (2005) * *'Living labs make it possible to bring users and technology together in an open-ended design process in real- life environments'* (Følstad, 2008) (Bernhaupt *et al.*, 2008)	This study focused on the research and elaboration of concepts and strategies of home information systems, in addition to the development of a HEMS, which was analyzed with a grounded approach. The aim was to educate house holders about domestic electricity consumptions to persuade them to consume less. The feedback about the household and appliances consumptions was provided through TVs, PCs, smart phones and tablets. The HEMS gave the householders a better understanding of their own energy consumptions and improved their theoretical knowledge about energy. In the end, the result of this longitudinal qualitative study was that the householders were able to understand their energy flows and use that information to manage the energy consumptions.
ZEB	X	X	Residential building	*'A Living Lab can be defined as user-centered experiment with the aim of testing a particular technology, solution, idea or policy in a real-world condition, where the aim is to induce social and/or technical change'*	The ZEB Living Laboratory aims to balance the greenhouse gas emissions of operations with the building's renewable energy generation. In this case, taking advantage of daylight availability of a Nordic climate and by improving the use of renewable energy sources, it reduces the energy demand of the building while maintaining the thermal and visual comfort of the users. The ZEB had a monitoring system for electrical and thermal energy use and recorded indoor and outdoor environmental conditions. In this study, user behavior was monitored and, in order not to influence it and change their own habits, they did not receive specific instructions. Studies found that human behavior is hard to predict, because their interaction with the lighting system is due to other aspects and not to the actual natural light availability. In brief, there was no relation found between the natural light availability and use of artificial light in a residential building.

Name	Monitoring	Control	Type of Building	LL Definition [20]*	Summary
SUSLABNRW	x	x	Households, InnovationCity Ruhr and Living lab facilities	*'a user-centric innovation milieu built on everyday practice and research, with an approach that facilitates user influence in open and distributed innovation processes engaging all relevant partners in real-life contexts, aiming to create sustainable values'* (Bergvall-Kåreborn et al., 2009, 3) or (Schneidewind and Scheck, 2013)	This study suggests that technological efficiency innovations are not enough to achieve sustainable patters, and lifestyles and costumes need to be considered. The SusLabNRW in Ruhr, Germany, wants to find how energy and resources efficiency in buildings can be improved by making the users active in the process of heating and space heating, aiming to develop sustainable product service systems solutions. Researches revealed that 26-36% of home energy consumptions are caused by users' behavior, hence by optimizing it is possible to save energy. A three-step model of research was adopted consisting first in Insight Research followed by prototyping and finishing with field testing, in order to find Sustainable innovation for a comfortable indoor climate. However, the last phase could not be conducted. In the final analyses the empirical results support that the user's behavior is very important and are often underestimated.
Living Lab	x	x	Households	(Følstad, 2008) (Ståhlbröst, 2012)	The goal of the study is to find a general approach to decrease energy consumptions in personal homes in different European countries. Sessions for brainstorming and finding solutions were conducted in Norway, Sweden, Denmark, Lithuania and Iceland. The chosen approach was a concept developed at the Wireless Trondheim Living Lab (Andresen et al., 2007). They used the existing Wi-Fi as transport for AMS meter readings and provided an app showing real-time energy consumption and other power statistics. Also, the provided smart house technology enabled the users to control power devices through the mobile app. Overall there were not enough subjects of study to generalize.

All six studies have in common the aim of improving energy efficiency of buildings, in real-life scenarios, through different approaches. All aim to improve energy efficiency, using the Living Lab approach as a means to an end, improving user comfort levels.

The OU44 Building, was equipped with efficient technologies and helped create a new and improved model, the Energy Plus, which gave a more accurate value than the performance certification tool used in Denmark. The FZI house of Living Labs, where optimization strategies are developed, is equipped with automation, distributed generation, thermal and electrical storage and technologies and many of the devices and systems provide communication Interfaces for grid support. This Living Lab helps find solutions for problems like grid support, economic profit and self-consumption.

The first two studies use the Living Labs to test their approaches in real-life scenarios. The Longitudinal Living Lab Study of a HEMS even though it does not allow any control by the users, allows them to monitor the information. The Longitudinal Living Lab Study of a HEMS aims to educate the users about their electricity consumptions to reach energy efficiency. With a different approach, the ZEB study aimed to monitor the behavior of the users to see if there was any relation between their consumption habits and external conditions. In this case light consumption was the topic studied.

The SUSLABNRW study also believes that the user interaction is as important as the technological efficiency innovations adopted, and also aims to optimize human-behavior. The SUSLABNRW approach is allowing users to monitor and control energy consumptions by a remote application. Unfortunately, the testing phase of the SUSLABNRW study could not be conducted. With the same approach, the Living Lab Study also allows the users to monitor and control their energy consumptions by a remote application, unfortunately there were not enough subjects to reach any conclusions in their studies.

Following below, a more detailed description of each study for a deeper understanding of each approach.

The OU44 Building

The OU44 Building[21] is a highly energy efficient teaching building, which is located at the University of Southern Denmark in Odense. The OU44 Building operates as a Living Lab under the international research project COORDICY. The aim of the study is to improve energy efficiency of public buildings by enabling them to monitor, manage and control operations. For this propose the 8500m2 building uses energy efficient technologies such as ventilation units with heat recovery, LED lights, underfloor heating, PV modules, heating, lightning and electricity consumption sub-meters, and temperature, humidity, CO^2, LUX and PIR sensors on the room level [21].

In Denmark, there is a performance certification tool for buildings, BE10, which gives a static energy performance prediction but does not consider occupancy behavior and weather conditions. Thus, a dynamic holistic energy model (Energy Plus), was used to make a more precise evaluation. This model considers orientation and geometry, energy systems, building services, thermal envelope, constructions, occupancy behavior and weather conditions. OpenStudio and Sketchup Pro were also used for modelling and better Interface. A modelling and simulation approach given by Jradi et al. [22] which consisted of;

- collecting building information and data available,
- reading the building 3D model from the BIM delivered by the consultant company,
- defining the detailed energy model in OpenStudio,
- simulating the building energy performance employing a weather file and occupancy schedule,
- reporting the dynamic energy performance.

After simulations were conducted the conclusion reached was that the Energy Plus model allowed a better prediction of the building performance by 11% vs actual meters, whereas the BE10 models had a 55% energy performance gap.

FZI House of Living Labs (HoLL)

The FZI House of Living Labs[23] aggregates many Living Labs with the purpose of researching, developing and evaluating real-life scenarios. The Living Lab smart Energy investigates solutions for the future energy system. Hence, the labs are equipped with automation, distributed generation, thermal and electrical storage and technologies that enable more flexibility over energy supply and demand. Some of the equipment available in the lab is illustrated in figure 1.

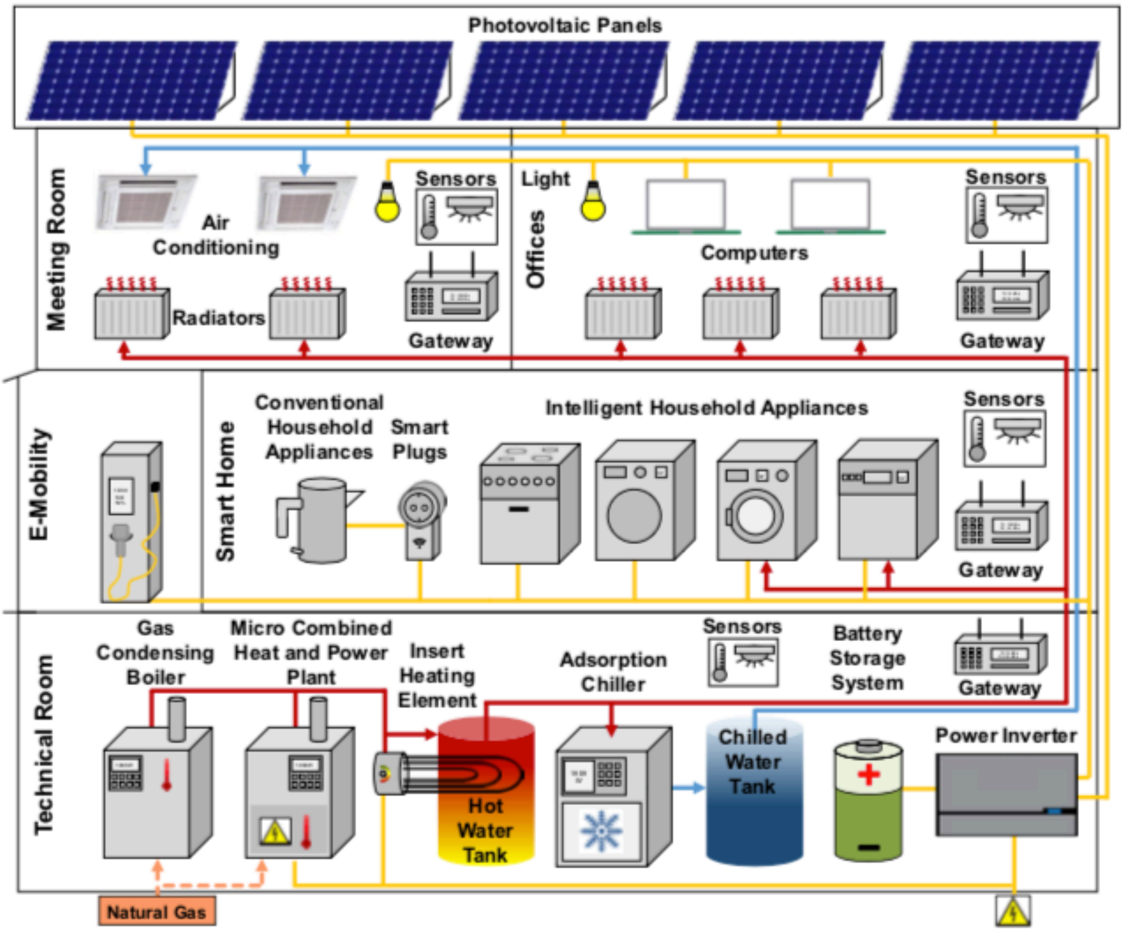


Figure 1 - Living Lab smart Energy equipment [23]

Because of the high energy demand in buildings, Building Energy Management Systems (BEMS) has a great potential to adapt the building's energy load to the overall state of the network, as well as to provide appropriate auxiliary services in future smart grids. The research focuses on efficient information and communication technologies (ICT) for integrating heterogeneous components into BEMS, as well as optimization strategies and algorithms for power systems and user interaction Interfaces.

Since the overall goal of the research is to provide flexibility for the power grid, many of the devices and systems provide communication Interfaces. The standardized integration of different communication protocols is one of the main focuses of the HoLL research. Therefore, it is equipped with heterogeneous communication systems. As the integrated optimization of multiple energy carriers is another focus of research, energy flows to electrical installations, heating, cooling and natural gas are measured, analyzed and controlled. A large number of different devices and building automation technologies provide a suitable research platform for various aspects such as standardized integration, interoperability, smart grid features and power management methods. Based on this platform, optimization strategies are developed to address different energy management goals, such as grid support, economic profit or self-consumption.

Longitudinal Living Lab Study of a HEMS

The Home Energy Management Systems (HEMS) [24]-[25] consisted of seven households in a Living Lab setting, which allowed the householders to monitor their energy consumption both in real time and in retrospective. This study focused on the research and elaboration of concepts and strategies of home information systems, in addition to the development of HEMS, which was analyzed with a grounded approach.

There were lacking ethnographic oriented studies that could answer not how feedback affected people but what people were doing with that information in their daily life. The aim was to educate house holders about domestic electricity consumptions to persuade them to consume less. The feedback about the household and appliances consumptions was provided through TVs, PCs, smart phones and tablets.

The HEMS gave the householders a better understanding of their own energy consumptions and improved their theoretical knowledge about energy. In the end, the result of this longitudinal qualitative study was that the householders were able to understand their energy flows and use that information to manage the energy consumptions. This means that the issue of energy literacy is a key element for the consumers participation eco feedback systems.

ZEB

The ZEB Living Lab[26]-[27]-[28] is located at the Norwegian University of Science and Technology in Trondheim, Norway. The goal of a ZEB building is to balance the greenhouse gas emissions of operations with the building’s renewable energy generation. In this case, reduce the energy demand of the building, maintaining thermal and visual comfort of the users, by improving the use of renewable energy sources and taking advantage of daylight availability of a Nordic climate.

The ZEB had a monitoring system for electrical and thermal energy use and recorded indoor and outdoor environmental conditions. In this study, user behavior was monitored and, in order not to influence it and change their own habits, the users did not receive specific instructions.

Human behavior is hard to predict, because user interaction with the lighting system is due to other aspects and not to the actual natural light availability. In brief, there was no relation found between the natural light availability and use of artificial light in a residential building.

SUSLABNRW

The integration of sustainable patterns of production and consumption in our society is a big challenge. The transition processes need to be designed, in which sustainable product service systems (PSS) are a promising approach. This study suggests that technological efficiency innovations are not enough to achieve sustainable patters, and lifestyles and costumes need to be considered. The SusLabNRW [29]-[30] in Ruhr, Germany, wants to find how energy and resources efficiency in buildings can be improved by making the users active in the process of heating and space heating, aiming to develop sustainable PSS solutions.

The Wood and Newborough (2003) research revealed that 26-36% of home energy consumptions are caused by user behavior, hence by optimizing it is possible to save energy. A three-step model of research was adopted consisting first in Insight Research followed by prototyping and finishing with field testing, in order to find Sustainable innovation for a comfortable indoor climate. Sadly, the last phase could not be conducted.

In the prototyping phase, some product solutions are currently being tested as assisting functions in heating and airing behavior:

- A wallpaper that functions as indoor insulation

- Smart home systems

- CO2 signal light, indicating the indoor CO2 concentration

- Combined sensor toolkit monitoring temperature, humidity and CO2 concentration, providing users with feedback. The toolkit records a baseline and data for comparison when using the product. In the final analyses the empirical results support that the user's behavior is very important and are often underestimated.

Living Lab Study

The reduction of energy consumptions is essential to reach a sustainable environment. Households hold 25% of energy consumption in Europe. The study by J. Krogstie, A. Ståhlbröst, M. Holst et all. [31] across a large scale of nations encounters a large variety of energy productions and costume consumptions patterns. In essence, the goal of the study is to find a general approach to decrease energy consumptions in personal homes in different European countries.

Sessions for brainstorming and finding solutions were conducted in Norway, Sweden, Denmark, Lithuania and Iceland. A concept was developed at the Wireless Trondheim Living Lab, Andresen et al., 2007 [32] consisted of using existing Wi-Fi as transport for AMS meter readings and provide an app showing real-time energy consumption and other power statistics. From the countries tested, 80 % of all households, have Wi-Fi installed already.

The provide smart house technology enabled the user to control power devices through the mobile app. Overall there were not enough subjects of study to generalize.

2.3 IOT

The concept of Internet of Things or IoT was first introduced in 1999 by Kevin Ashton [33]. He realized that Radio Frequency Identification Systems (RFIDs) and sensors together with Internet connectivity could allow computers to access information without human interaction. As technology evolved, the definition of Thing changed and the idea of allowing computers to detect information without the limitation of human intervention to feed data, remained [26]. Today, the IoT is used in a wide variety of fields and stands out as one of the most important areas in the future of technology[34]. More importantly, IoT brings intelligence into our environments by connecting everyday objects and allowing systems to learn from the collected data or even complete sets of tasks. Meaning Things can analyze the data, decide and act without human involvement.

IoT aims to provide Things in the world with Internet connectivity. The goal is to facilitate communication and interaction between Iot devices. In addition, Iot enables access and control to the Things in real time anywhere and anytime. In fact, the monitorization and control of Things can be done remotely through the internet. Being able to constantly track the devices can lead to improvements in performance and lower potential costs, by helping predict future outcomes and operation patterns.

Two key components in IoT are sensors, which detect changes in the evolving environment and send information of the change, and actuators, that move or control Things. IoT devices and machines are integrated with sensors and actuators and generate huge amounts of data. Users can make decisions on the data by using smart and analytical tools. These tools can be incorporated into IoT devices so that real-time decision making can take place. The collected data can be used to discover and solve problems to increase user satisfaction, and to provide value-added services to users.

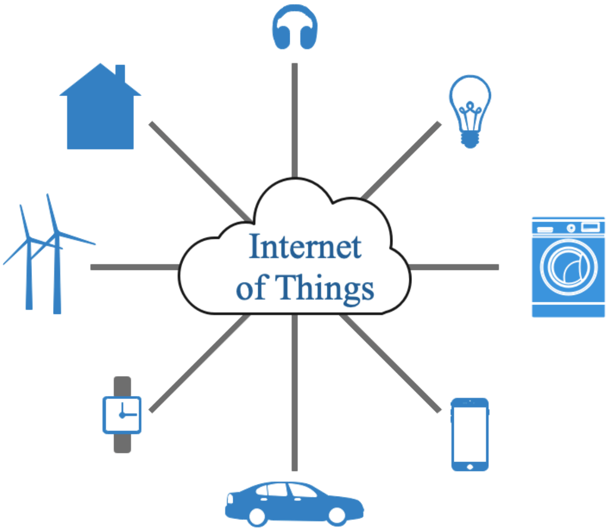


Figure 2 - Internet of Things

The Internet of Things is influencing the current lifestyle from the way users react to the way users behave. The giant network of IoT connected devices gathers and shares data about how they are used and the environment in which they operate. Sensors can be imbedded in physical devices such as mobile phones, electrical appliances and almost everything that is possible to came across in day to day life. These sensors constantly emit data about the working state of the devices. IoT provides a common platform for all the devices to store their information and share a common language for all the devices to communicate with each other. The IoT platform integrates the collected data from the various sources and performs further analytics. Analytics performed on the data result in valuable information that is shared with other devices for better user experience, automation and improve efficiency. With smart appliances, smart cars, smart homes and smart cities where IoT is redefining the current lifestyle and transforming the way users interact with technologies. Business insider Intelligence estimates that there will be more than 64 billion IoT devices by 2026, up from about 10 billion in 2018, and 9 billion in 2017 [39].

As was shown before, IoT brings the benefit of sharing and collaboration between people, Things and between people and Things. More opportunities to share information increase awareness of situations and avoid delay and distortion of information. Iot will be used to monitor and control the conditions by distributing Things that can help gather real time information and act on a heat pump.

2.4 Discussion

Concerns about climate change are reaching worrying levels because of its effects on the planet. Contemporary life is fully dependent on energy. Hence the need to test new technologies in energy efficiency and energy flexibility. By increasing energy efficiency, is possible to reduce consumption and, by using energy flexibility, is possible to make its use more flexible. In this work energy flexibility is quantified by flexibility in operation and used to change the operation of controllable devices in order to reduce electricity related costs.

As noted in the literature review and background information, energy flexibility considers user comfort levels, making Living Lab one approach to test new technologies like flexible systems. It is also mentioned in the SUSLABNRW study, that the user's behavior is very important and often underestimated. Not only is it important to test new technologies in real-world scenarios using Living Labs, but also make the test of new technologies accessible to others, as user behavior contributes to the optimization process. That is why making Living Labs also remote is so important, so users can access information over the internet, be informed and make decisions about the information retrieved. Even though, there are some studies being conducted on the subject, there still seems to be the lack of research on remote laboratories and the remote laboratories benefits. To fill the gap in research, this thesis will provide more opportunities for future remote Living Lab studies, where the user can be the center of the research. The definition of Living Lab used in this paper is a mixture of the definitions presented earlier in which Living Lab is a design research methodology that aims to research, develop and evaluate real-life scenarios through the involvement of conscious users.

3 Flex Lab

The conceptual model presented in Section 3.1, of which the motivation, objectives and background review are described in chapter 1 and 2 respectively, is used to establish the Flex Lab's layers and functionalities in order to remotely control an office and study the benefits of energy flexibility by applying demand response methods. A thermal model is also provided in Section 3.1, to justify the choice of the Living Lab's measured variables. The conceptual model supports the architecture of the Flex Lab described in Subsection 3.1.1, which follows a modular approach that can be applied to any office building in which each component of the system can be replaced according to the available technologies. The system allows the monitoring of inside and outside conditions of the office building and allows the control of some devices available in the office. The implementation of the Flex Lab is described in Section 3.2.

3.1 Conceptual Model

As mentioned before, energy flexibility is used by demand response methods to modify the energy demand profile of e.g. buildings. In this work, a system entitled Flex Lab is developed to support the development and assessment of demand response methodologies in a Living Lab environment where the occupant's preferences are considered. This system is intended to be applied to office buildings and focuses on the study of energy flexibility. Thus, the Flex Lab has two main components; a Living Lab and a Remote Control Unit (RCU). The occupants assume a central role interacting with the Flex Lab and with the Remote Control Unit. Figure 3 shows the high-level conceptual model of the Flex Lab.

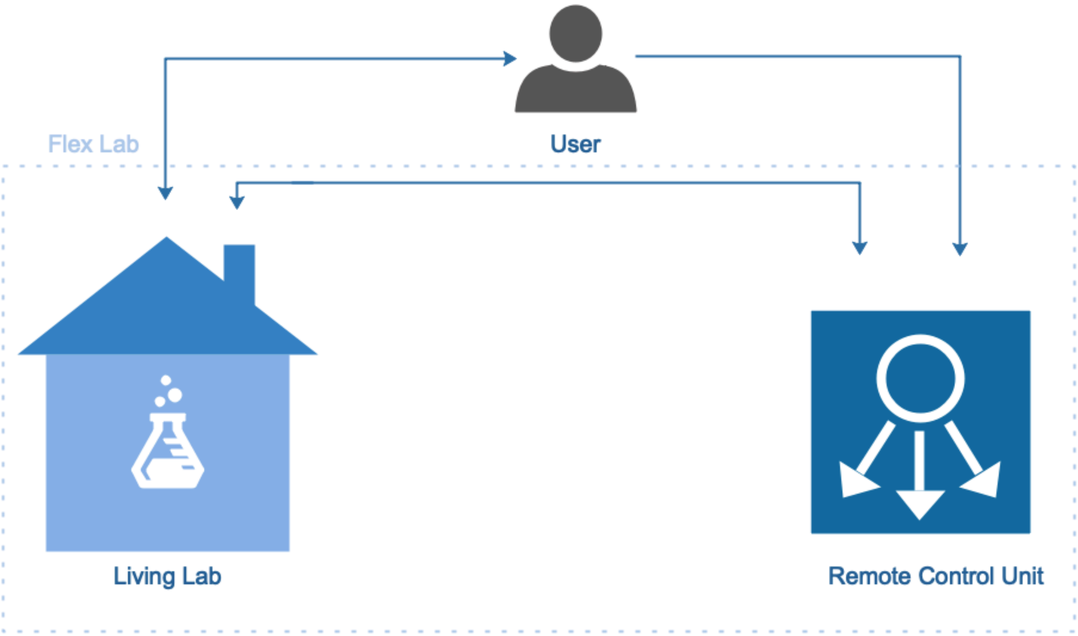


Figure 3 - Conceptual Model

In the proposed system, the user is the entity responsible for developing and/or assessing the algorithm, in the RCU, that explores the existing energy flexibility in the Living Lab. Assuming an important role by establishing a bidirectional communication with the Living Lab and a one way communication with the RCU. The user is also responsible for ensuring the communication between the Living Lab and the RCU when implementing the demand response algorithm. As the Living Lab and the RCU are independent of each other, the proposed system offers the possibility of controlling the Living Lab remotely, so the user may or not be the Living Lab occupant.

Two functionalities are offered to the user by the Flex Lab; the possibility of monitoring the Living Lab conditions and set the operation of existing controllable devices according to the control algorithm to be implemented in the RCU. The user decides the demand response algorithms and configures them in the RCU. Since the Remote Control Unit and the Living Lab are independent, they can communicate only after the user has chosen a method to establish communication. If communication is possible, the RCU collects data from the Living Lab and responds with the information that controls the controllable devices available in the Living Lab. The Living Lab can be any office building with controllable devices, sensors and actuators, that are capable of communicating using the Internet of Things paradigm and offering energy flexibility for the demand response methods.

To better understand the Living Lab thermodynamics and offer the best conditions to the occupant of the office building, while being efficient, the model proposed by R. C. Larson and F.C.Schweppe [36] is used. The model considers the space to be composed by the building, the equipment and the occupants and for the needed purposes certain assumptions had to be made. The thermal mass of the building was considered to be limited to the thermal mass of the air, where only the outside temperature and air conditioning are capable of changing the internal temperature of the building. The building was considered to be a single space where the internal heat sources of the space were neglected as well as the circulation effects assuming uniform temperature inside.

The mathematical formula to calculate the energy balance of the Living Lab is show in (1).

$$T_{n+1} = \varepsilon T_n + (1-\varepsilon)\left(T_n^0 \pm \eta \frac{e_n}{A}\right) \tag{1}$$
$$(+: heating, -: cooling)$$

In (1), T_{n+1} is Living Lab inside temperature in time-step $n+1$, ε is the inertia factor, T_n is the temperature inside the Living Lab at the time-step n, T_n^0 is the effective outside temperature in period n, e_n electric power input in period n, which is delivered by a controllable device present in the Living Lab, A is the overall thermal conductivity, and η is the coefficient of performance (cooling) and thermal conversion efficiency (heating). From (1) it is possible to understand the functioning of the system. The higher the energy used by the controllable devices, the greater the difference between indoor and outdoor temperature. Consequently, the bigger the difference of temperatures, the bigger are the losses of the system.

3.1.1 Architecture

In the proposed conceptual model, the Flex Lab consists of a Living Lab and a Remote Control Unit, both independent from each other to allow the user to be able to control the Living Lab remotely and study the benefits of energy flexibility, without direct access to a physical Living Lab. Figure 4 presents a modular architecture chosen to give flexibility when implementing the Flex Lab in a real-case scenario. The Flex Lab architecture is constituted by following modules: Remote Control Unit, Interface, data storage module sensors and actuators. While the Living Lab incorporates the Interface, data storage module and Things, the Remote Control Unit is a standalone module. Each module constitutes a set of independent components and each component can be implemented according to the available technologies.

In Section 2.2, six studies were reviewed where the Living Lab approach aims to improve energy efficiency of buildings in real-life scenarios while improving occupants' comfort levels. Considering that none of the approaches found gave the possibility to remotely control the Living Lab, the Flex Lab system aims to provide remote control of an office building and allow the user to study the benefits of energy flexibility while applying demand response methods and respecting the comfort levels of the occupants.

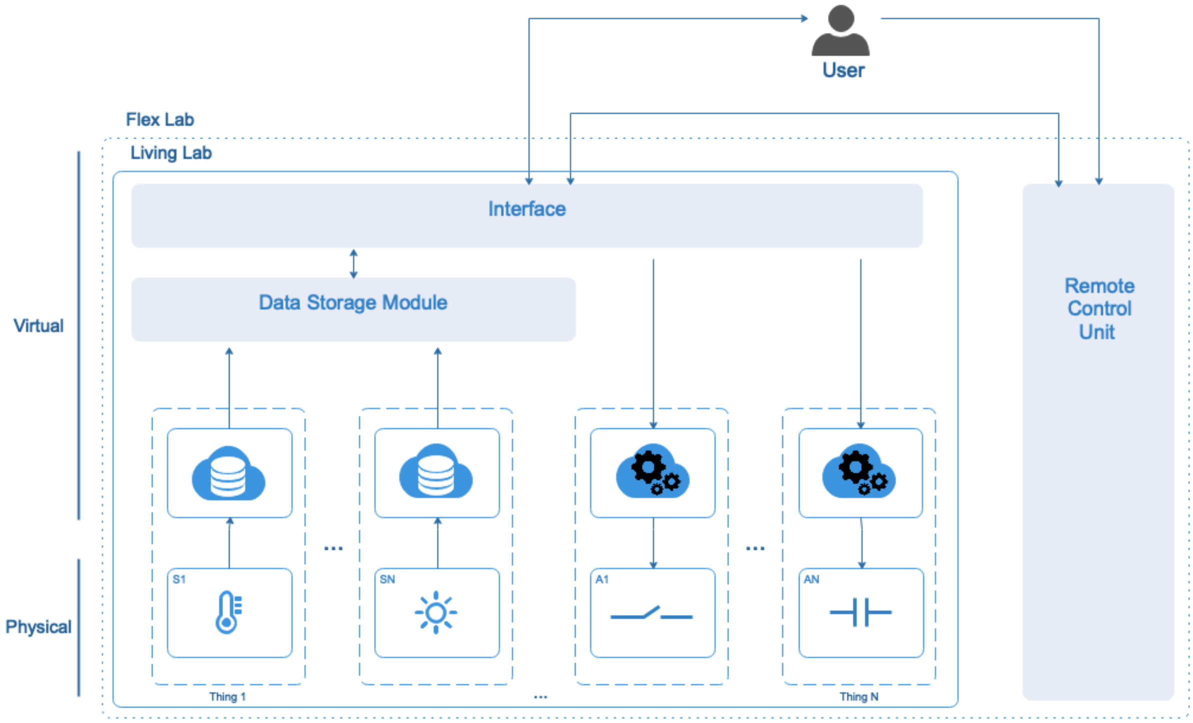


Figure 4 - Architecture of the system

Another relevant concept is the one referred as Thing, introduced in Section 2.3, and alludes to the benefits of accessing and controlling connected devices, or Things, in real time, anywhere. In the described architecture, the Living Lab is composed of connected Things, that can be sensors and actuators. The virtual and physical representation of the devices represents a Thing.

The physical layer of the architecture consists of physical sensors and actuators, while the virtual layer consists of the virtual representation of the physical devices, the data storage module, the Interface and RCU. The sensors are responsible to send the collected information of the Living Lab conditions to a data storage module. Once the collected data are updated by the sensors in the system, the Interface is used to monitor the virtual representation of the devices. Afterwards a graphic image is created and available in the Interface to be analyzed and visualized from anywhere and anytime, offering information about the Living Labs conditions. The actuators are connected to the controllable devices and are the ones responsible to act on them. The virtual representation of the actuators is created by the Remote Control Unit, where rules carry out the processing of Interface data and send back the orders that set the behavior of the controllable device.

In this work, rules are intended to enforce demand response algorithms, which are implemented in the RCU using energy flexibility. Energy flexibility was introduced in Section 2.1 as being the capability of a building to change, adapt or move its energy consumption profile. In this architecture energy flexibility is used to change the operation of the controllable, expecting to modify the office consumption profile.

The user plays an important role in the Flex Lab operation, communicating with the Living Lab and the RCU. Since improving the user experience is one of the focus of the study, the user is given full control of Living Lab's comfort preferences, which are set according the occupants' needs. User communication with the RCU is unidirectional, as the user defines the demand response algorithms, according to the Living Lab's occupants comfort preferences. The user can also receive and monitor Flex Lab information through a graphical user Interface with whom establish a two-way communication. More specifically, the user makes requests on the Interface for specific information and the Interface shares the stored information with the user.

In the developed architecture, the internal and external conditions of Flex Lab are collected. The external variables considered for the study were the outdoor humidity, the outdoor temperature and the solar irradiance. For the internal variables the indoor temperature, the indoor humidity and the current were considered. As explained further in Section 3.2 temperature and humidity are very important to ensure comfortable conditions to the Living Lab's occupant. In addition, the indoor and outdoor temperature were considered to assess system losses, which, according to the thermal model presented in the conceptual model, the larger the difference between internal and external temperatures, the greater the system losses.

The role of Things in the proposed architecture is to collect data and act on the system. Sensors are responsible to send data to the system's Data Storage Module, where the information is stored and then displayed in the Interface as a graphic image. The communication between sensors and the Data Storage Module is unidirectional because the sensors only sense and send data with no need for communication in the opposite direction. On the other hand, actuators are responsible to act on the controllable devices present in the Living Lab, receiving data directly from the Interface communicating unidirectionally. While sensors provide data to the Interface, actuators receive information from the Interface which is sent by the RCU.

The Interface layer enables communication between the Living Lab and the outside world, ensuring communication with the user and the RCU. Through the Interface, the user monitors the Living Lab's conditions and the RCU sends the control actions associated to the DR algorithms to the Living Lab. Communication between the Interface and Data Storage Module is bidirectional, as the Interface sends a request to this module requesting specific data and the database sends the data back to the Interface.

As mentioned in the conceptual module, the RCU is an external entity fully independent of the Living Lab, only communicating with it through the Interface. In addition, to have a fully functioning RCU, control rules must be defined and information must be available on the Interface to enforce them. The RCU is responsible for fetching data through the Interface, applying demand response algorithms, and sending control instructions (actuator behavior-related control commands) back to the Interface through which the virtual representation of actuators is actuated. The definition of the RCU rules to be applied in the office building according to the occupant preferences of Living Lab is done by the user, who also decides the demand response algorithms that will use energy flexibility. To improve the process, the Living Lab Interface can send triggers (procedural code that is automatically executed in response to certain events) to the remote control unit once data is updated. The triggers ensure that the parameters are updated on data insertion, so that the behavior of the internal conditions of the Living Lab are as accurate as possible.

3.2 Implementation

According to the conceptual model developed in Section 3.1, Flex Lab implementation takes place in an office building in office at UNINOVA, where the objective is to study energy flexibility. At the implementation level there is an interest in monitoring indoor and outdoor conditions while acting on the controllable device. This actual implementation aims to exploit the energy flexibility of a heat pump by using demand response methods to minimize electricity related costs, while respecting the occupants comfort preferences.

Figure 3 presents the Flex Lab conceptual model, composed of two main components, namely: the Living Lab and the Remote Control Unit. The Living Lab was implemented in an office building where the devices are located, with the heat pump being the only controllable device available that offers energy flexibility. The implementation of the Remote Control Unit was support by MATLAB software [37] and used to apply the control algorithms.

After modelling the internal behavior of the heat pump and the Living Lab, it is possible to determine the use of energy flexibility. This concept is based on the principle of changing the operation of the heat pump by changing its state from on to off. Changing the operation of the heat pump changes the heat pump energy consumption profile.

The architecture of the system is presented in Figure 4, where the Flex Lab is divided in two layers, one physical and one virtual (each has several modules). While the Interface, data storage module, and RCU belong only to the virtual layer, the Things have a physical and virtual representation. Flex Lab's physical layer implementation consists of sensors and actuators, which correspond to the physical part of Thing.

The Flex Lab’s virtual layer implementation was supported by the integrated Thingspeak platform environment [38]. Data analysis, processing needs and easy integration with the physical layer constitute some of the reasons that lead to the choice of the Thing Speak platform. The Thing Speak platform enables easy communication with the physical layer, through a call to the REST API and the appropriate API key. In addition, communication between the Living Lab and the user is established through the Interface provided by the Thing Speak platform. The Interface is where the virtual representation of Things can be monitored, providing easy graphical representation of the resulting data published by physical devices. In brief, the Think Speak platform includes the Interface, data storage module and virtual representation of the Thing, while the

Remote Control Unit was implemented using MATLAB. The Thing Speak platform also allows the use of MATLAB analysis directly from the Interface, facilitating analysis execution and gathering information about the data. This way, by reading directly from the Thing speak URL channel it is possible to read data stored in Thing Speak channels and react.

Three channels were created on the Thing Speak platform for this implementation. The Inside channel holds information from the inside of the Flex Lab, where two sensors (temperature/humidity and current) send the information to three different fields of the Inside channel. There is a field for storing the inside temperature, another for inside humidity and another for storing the power consumption. Figure 5 shows an example of the inside channel where temperature and humidity are visible.

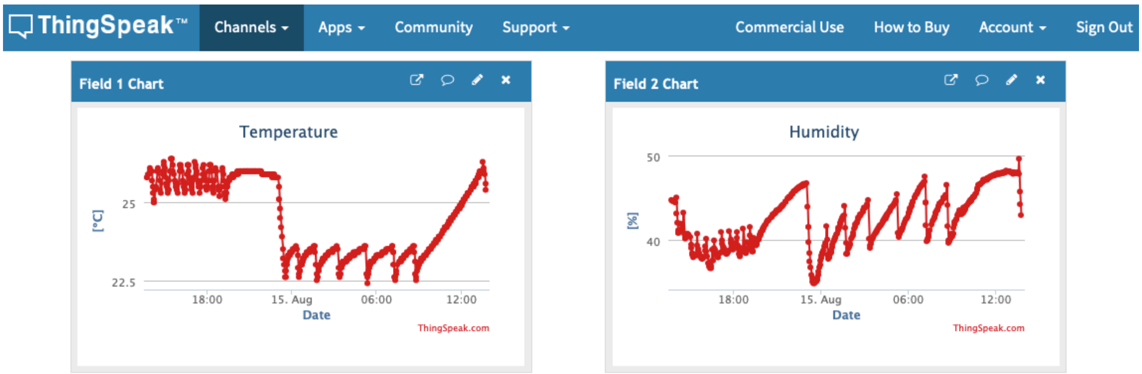


Figure 5 - Thing Speak Inside Channel

The Outside channel holds the outside information of the Flex Lab, where three sensors (temperature, humidity and image of solar irradiance) send the information to the data storage module which will be available in three different fields of the Interface . One field keeps the outside temperature, another the outside humidity and the third field keeps the output of the photovoltaic cell, positioned on the outside of the living lab window.

The Control channel keeps the Control information in a unique channel field. The RCU sends to the control channel the actuation commands to control the heat pump and the actuator then reads the control commands from the Interface control channel to act on the heat pump. In order to make a wireless connection between the sensors/actuators and Thing Speak Interface, wi-fi modules were chosen.

In total five components were installed of which four are sensors and one an actuator. The implementations were ensured by Arduino Uno microcontrollers connected to sensors, actuators and wi-fi modules. To achieve this implementation, three installations were made with the total of four Arduinos, two of them are for data acquisition only, another just to send information via wi-fi to the platform and a fourth one to actuate on the controllable device, in this case the heat pump available in the office. The supply voltage from the grid was considered to be 230 V. The USB power converter is used to power the 5 V Arduinos of both the outside installation and actuation installation and a transformer with an alternating current to direct current converter (AC / DC block) was used to power the inside installation.

In order to gather the Flex Lab's external conditions, equipment was installed on the outside of the Living Lab's window. In this case, the physical installation consists of two sensors that establish a unidirectional communication with the platform, where a virtual representation of the physical Thing is displayed. However, to enable communication with the virtual layer and to power the sensors an installation with an Arduino Uno, an electrical circuit plus a wi-fi module was used. As mentioned in the architecture description, the outside conditions comprise the temperature, humidity and output of the photovoltaic cell. A scheme of this installation is represented in figure 6. Table 3 presents the list of hardware components for the installation.

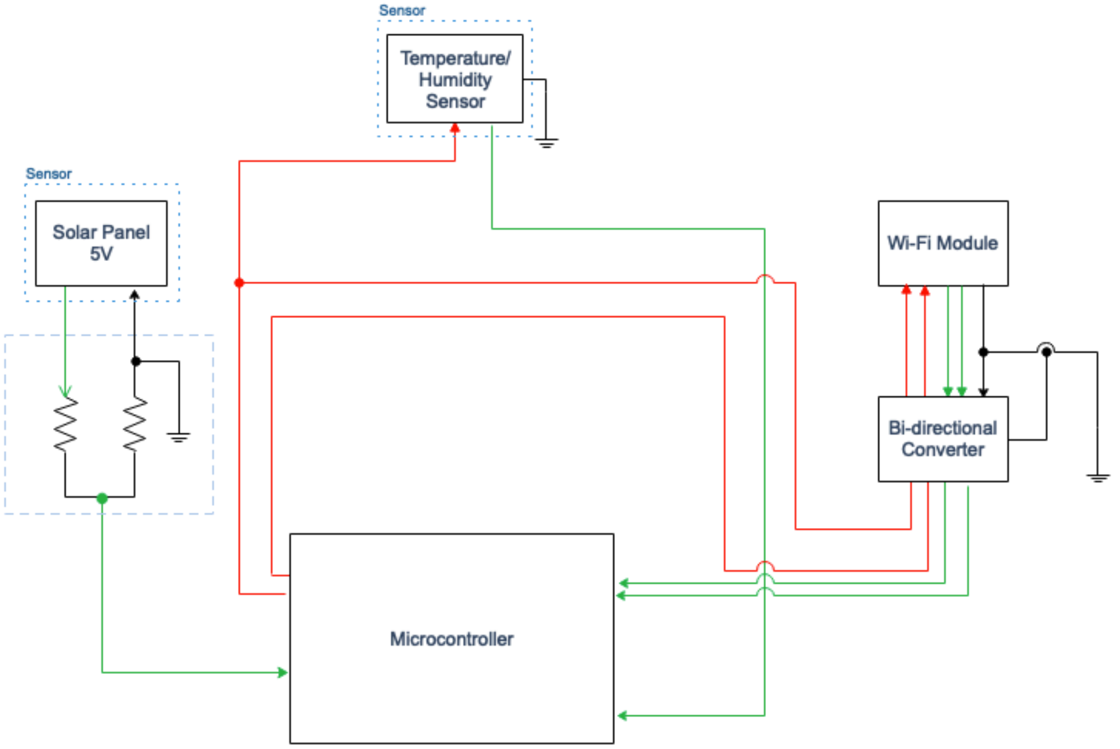


Figure 6 – Diagram responsible for the Living Lab outdoor conditions

Table 3 - Components used in the implementation of the installation responsible for the outdoor conditions

Hardware components	Model
Wi-fi module	ESP8266
Microcontroller	Arduino Uno
Sensor of temperature and humidity	DHT22
Resistor 39 ohm e 15 ohm	/
Jumper wires	/
Breadboard	April
Bi-Directional Converter Module	SparkFun Logic Level Converter - Bi-Directional
Solar Panel 5 V Cell (11cm x 6.9cm x 0.3cm)	/

The wi-fi module allows the integration of the physical part of the sensors and actuator with their virtual representations. The wi-fi module used was the ESP8266 with maximum working Voltage of 3.6V, which is a small module that allows microcontrollers to connect to a Wi-Fi network and make simple TCP/IP connections used to interconnect devices to the internet, by using AT style commands. The Arduino Uno microcontroller is used to power the ESP8266 Wi-Fi module but because the 3.3 V pin would not have enough current to power the ESP8266, a logic level converter, which steps down a signal from a higher voltage to a lower voltage, was used to make the conversion. The central pins of the logic level converter are used to connect each side to a power source of the target voltage, namely: 3.3 V on the low side which will be connected to the wi-fi module and 5 V on the high side which will handle communication signals to and from the Arduino.

A solar cell was used to have an indirect quantification of the solar irradiance. The cell ground wire is connected to the Arduino ground pin and the VCC wire is connected to the analog pin A0 of the Arduino through a resistor. The resistance has been sized to obtain the maximum power point at standard test conditions. Solar cells generate energy by converting solar energy from the Sun into electrical energy (the higher the energy from the Sun, the higher the voltage produced will be). The Arduino analog reference voltage is 5 V and the maximum voltage output of the solar cell is 5V.

The DHT22 sensor is used for monitoring the outdoor temperature and humidity of the Living Lab. The DHT22 consists of a temperature sensor with an operating range between -40~125 ºC and humidity between 0-100% RH. This sensor sends a digital signal to the Arduino module, being in this case connected to the digital pin 2. This signal is processed and converted back to temperature and humidity via software using the code present in the Arduino module. The block diagram that represents the code implemented in Arduino that controls the two sensors responsible for collecting information from the living lab's external conditions is shown in figure 7.

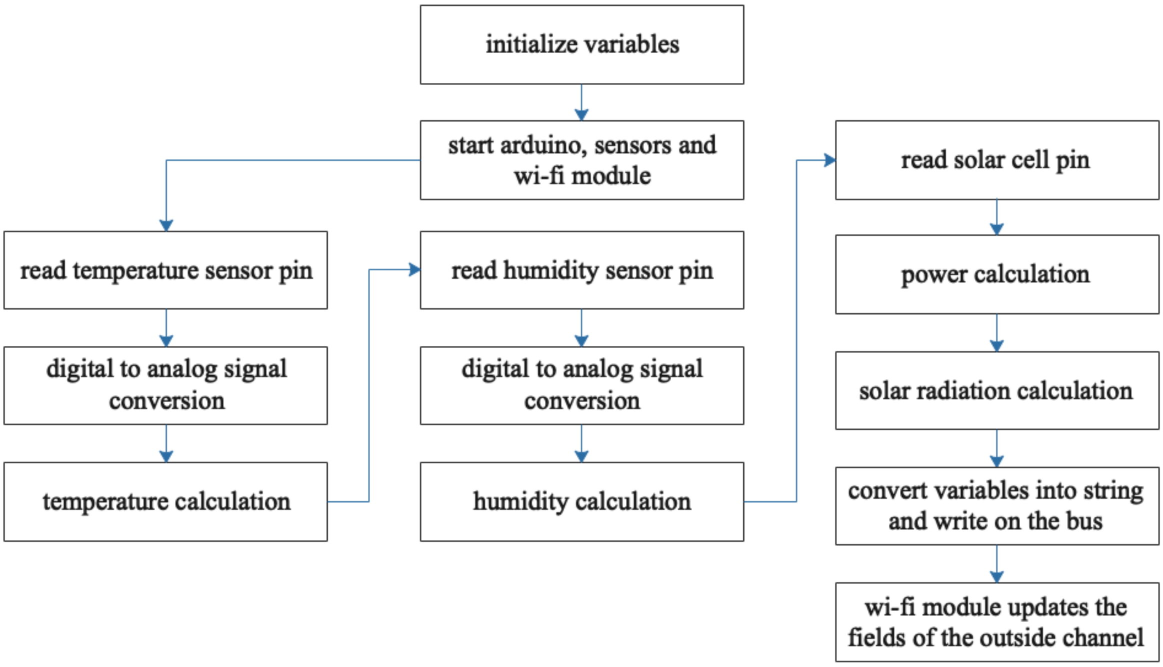


Figure 7 - Block diagram responsible for collecting information from outside the living lab

Living Lab's indoor information collection is done by two sensors. It has a sensor responsible for collecting temperature/humidity and another for current, all connected to the Arduino Uno microcontroller. This Arduino is connected to a second Arduino Uno which is connected to a wi-fi module that sends the sensors information to the inside channel in the Thing Speak platform. The inside installation is depicted in the figure 8. Table 4 presents the list of hardware components for the inside installation.

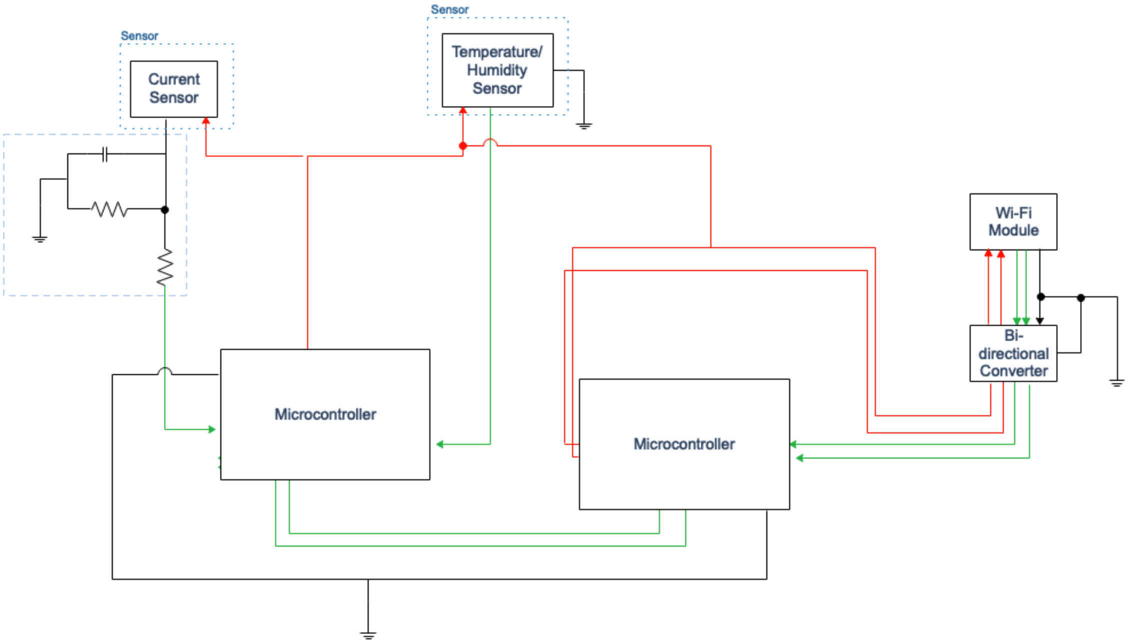


Figure 8 - Diagram responsible for the Living Lab indoor conditions

Table 4 - Components used in the implementation responsible for the indoor conditions

Hardware components	Model
Wi-fi module	ESP8266
Microcontroller	Arduino Uno
Sensor of temperature and humidity	DHT22
Resistor	/
Jumper wires	/
Breadboard	April
Bi-Directional Converter Module	SparkFun Logic Level Converter - Bi-Directional
AC Current Sensor	Non-invasive AC Current Sensor (30A)

The sensor responsible for monitoring the indoor temperature and humidity of the Living Lab is identical to the one described in the previous installation (for the external conditions), as well as the Wi-Fi module. This installation has two Arduinos, where one is in charge of collecting data from the sensors, while the other is responsible to send the data through a Wi-Fi module to the virtual level. Another addition to the installation is a non-invasive current sensor with a reading capacity of up to 30 A that generates at its output an alternating voltage analogue signal ranging from 0 to ± 1 V, proportional to the current value at its input. The block diagram that represents the code implemented in the two Arduinos and controls the two sensors responsible for collecting information of the Living Lab's indoor conditions is shown in figure 9 .

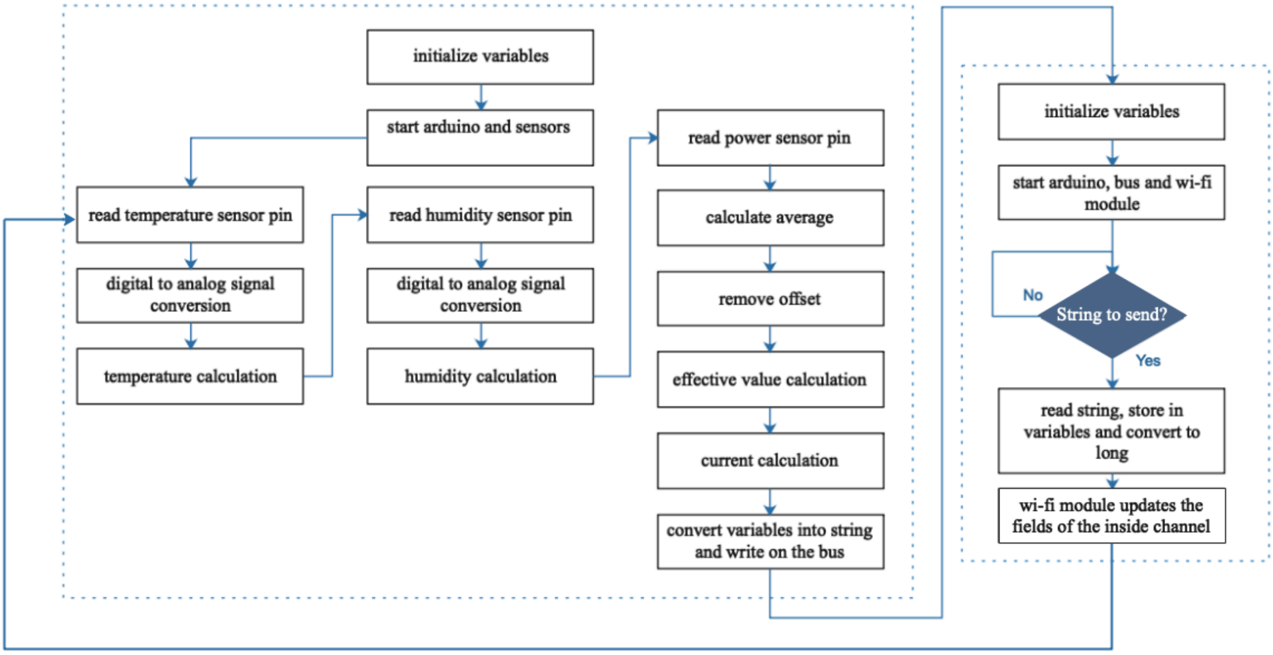


Figure 9 - Block diagram responsible for collecting information from inside the living lab

The actuation process is performed by controlling the electrical power consumption of the controllable device, in this case is performed by hardware, altering the behavior of the heat pump and consequently changing the indoor temperature conditions. The responsible installation contains an Arduino connected to a wi-fi module, just like previous installations, but instead of sending information to the interface, this time it gets the interface information, in particular the control field of the control channel of the ThingSpeak Platform. With the collected information, the actuator acts on the heat pump enabling or disabling it when necessary. A representation of the installation can be seen in the figure 10. Table 5 presents the list of hardware components for the implementation responsible for the actuation.

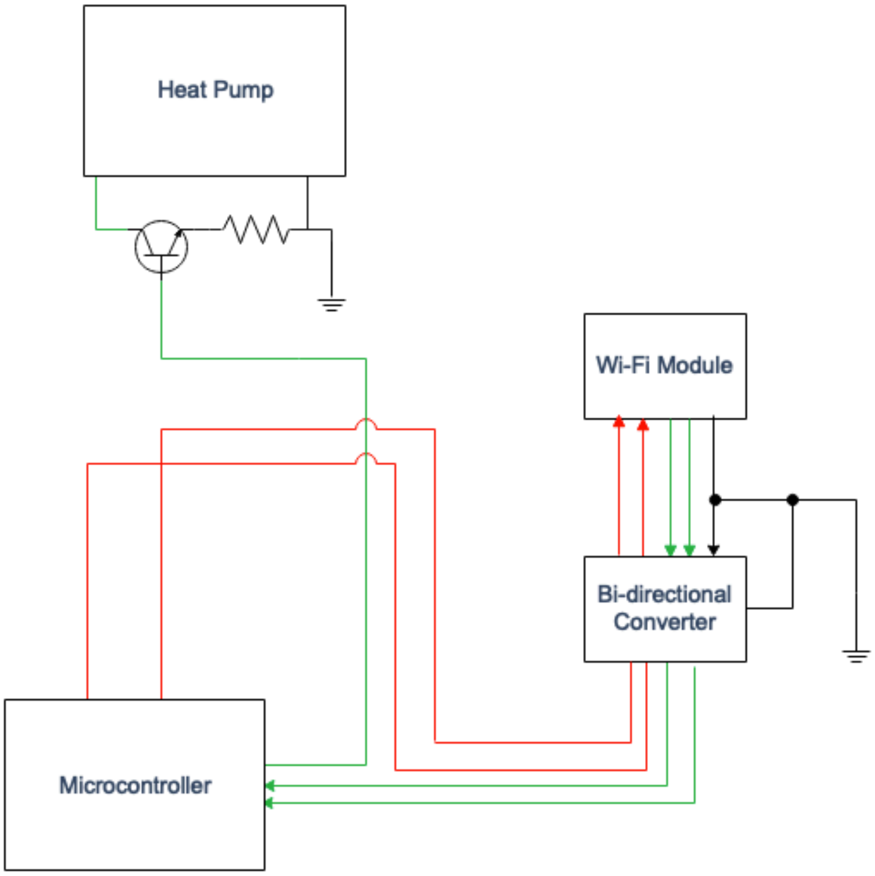


Figure 10 – Diagram responsible for the Living Lab actuation

Table 5 - Components used in the implementation responsible for the actuation

Hardware components	Model
Wi-fi module	ESP8266
Microcontroller	Uno
Resistor 1K ohm	/
Jumper wires	/
Breadboard	April
Bi-Directional Converter Module	SparkFun Logic Level Converter - Bi-Directional
Npn transistor	BC547
Heat pump	Panasonic CS-A93KE

The actuation installation, illustrated in Figure 10, consists of a circuit with a common emitter assembly of an NPN bipolar transistor which is responsible for driving the control signal from the Arduino module to the heat pump. In this case, the Arduino module in normal circuit operation places 5 V on the transistor base, which causes it to saturate, causing the voltage at the collector output to be approximately 0 V. When given the control instructions to open the circuit, the Arduino places at the base of the transistor 0 V. This makes the voltage in the collector approximately equal to the power and since the transistor is not saturated, there is no current flowing from the collector to the emitter.

Knowing how to control the circuit and how the controllable device behaves, by events, the Arduino's code was implemented so that when the Arduino Uno reads a change from 0 to 1 on the control channel, it places 5 V on the digital pin 12, for 2 seconds, to start the operation of the device. Because the heat pump works by events, when the Arduino Uno reads a change from 1 to 0, it places again 5 V on the digital pin 12, also for 2 seconds, to interrupt the operation of the device. The block diagram representing the code implemented in this installation is detailed in figure 11.

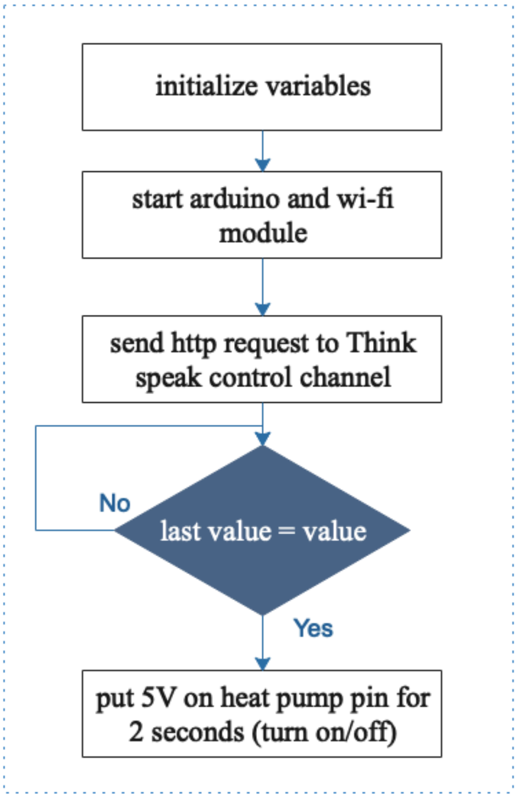


Figure 11 – Block diagram responsible for the actuation of the heat pump

The heat pump available in the Living Lab is a Panasonic CS-A93KE and in this case it is only used in cooling mode. A heat pump is a two-component appliance that uses electricity and refrigeration technology to provide cooling and heating. The first component is the condenser unit that is usually located on the outside of the installation and provides the heating or cooling. The second component, the evaporator, is located on the inside and brings the hot or cool air into the room. A heat pump uses a refrigerant to move heat from one location to another. In cooling mode, the compressor forces the high temperature, high pressure vapor into the reversing valve. The reversing valve reverses the vapor to the outdoor unit of the heat pump. The fan of the outdoor unit flows outside air across the heat exchanger. The air will be at cooler temperature so it carries thermal energy of the refrigerant away. The coolant condenses as it loses its thermal energy leaving as a high pressure cooler liquid. The coolant is then expanded, decreasing the temperature even more. Then the coolant is moved to the indoor unit of the heat pump, where the fan then forces the indoor air to go through the coil. The inside temperature in contact with the cool coolant causes the heat transfer from the air into the cooler, lowering the inside temperature. The coolant then goes back to the compressor to repeat the process. In heating mode, the process is reversed, transferring cold air outside of the room and returning warm air to the inside. Heat pumps have a high efficiency rate because they only use electricity for power rather than for generating heat. In heat pumps the electricity consumed is only used to power the two fans (evaporator and condenser), compressor and pump that are shown in figure 14.

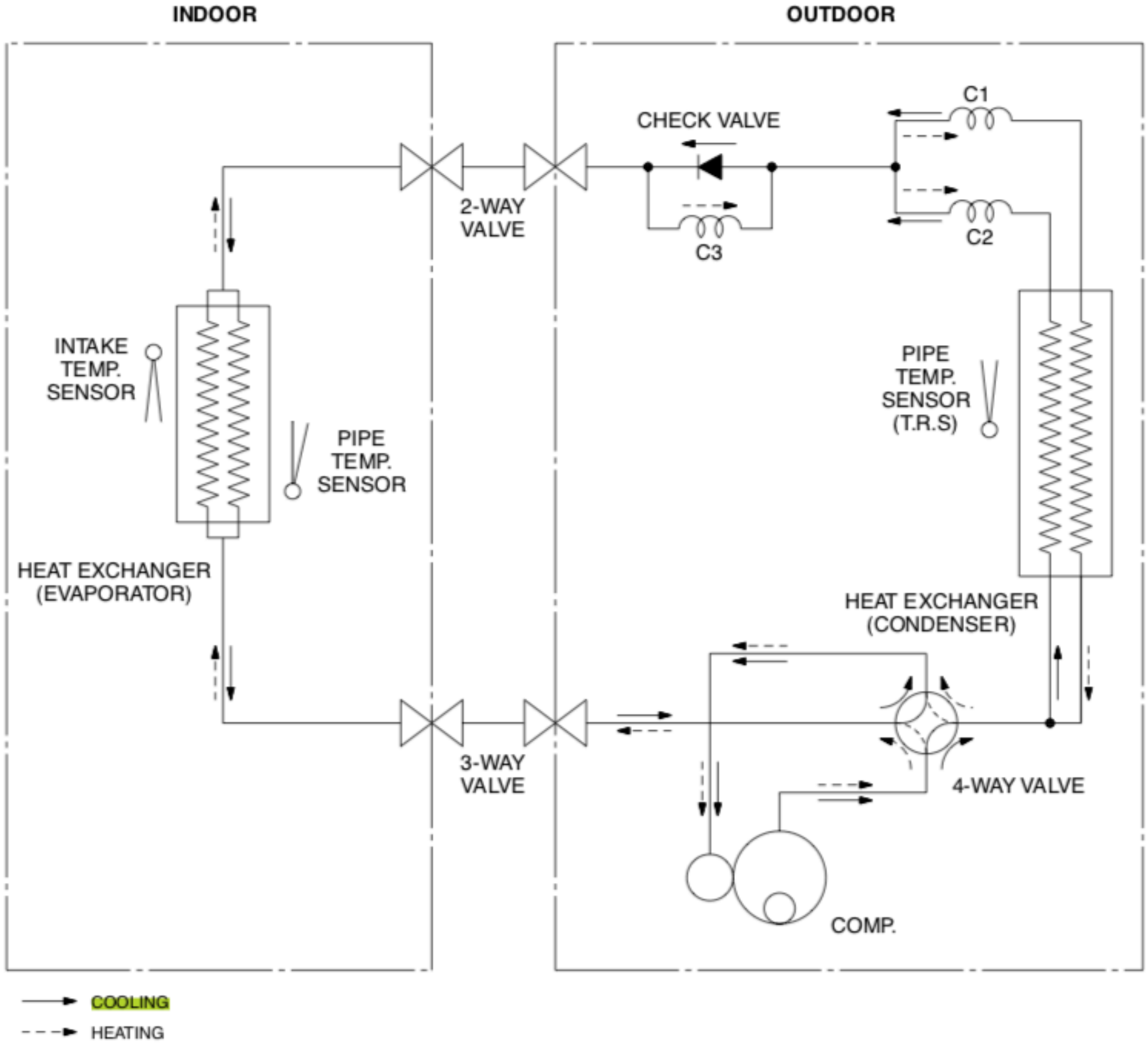


Figure 12 - Heat pump operation diagram

The demand response method is programed on the Remote Control Unit using MATLAB software. MATLAB reads the necessary information from the channels and decides the actions to give to the actuation module, introducing the response in the control channel. This response is done on data insertion, every time a channel is updated with the

Things data, the MATLAB analysis is triggered. The rules defined in the Remote Control Unit were specific for the heat pump present in the considered office. In this case, set the response to 1 to turn on the device and 0 to turn off. The block diagram from the Remote Control Unit installation behavior is detailed in figure 13.

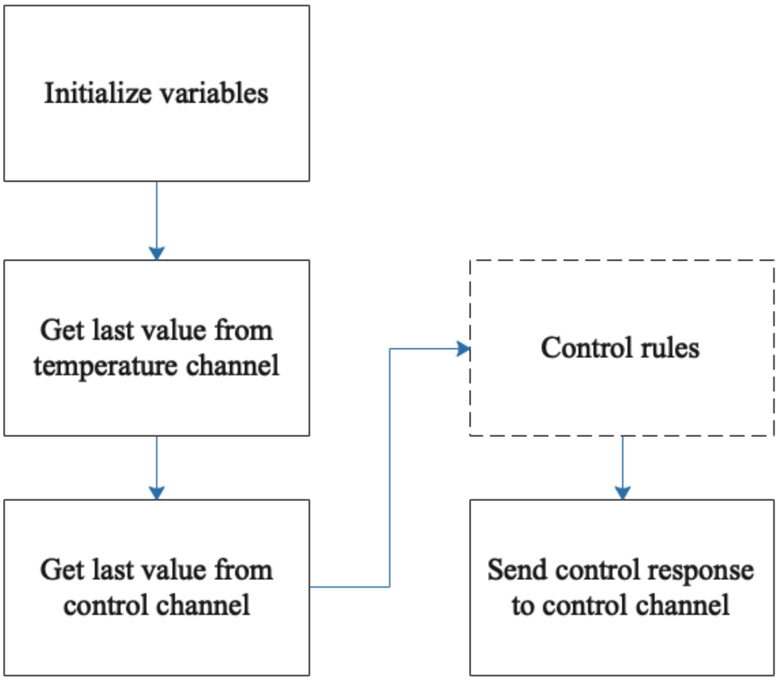


Figure 13 - Remote control unit

4 Results and Analysis

The Flex Lab, whose development is described in Chapter 3, is used in this work to study the energy flexibility offered by a real office building located in Portugal. The description of this case study is provided in Section 4.1 and the considered scenarios, which are related with the operation of the controllable device, are presented in Section 4.2. The collected results are presented in Section 4.3, together with the respective analysis.

4.1 Case Study

The Living Lab defined for the case study is an office at UNINOVA (Figure 14). The Flex Lab system is deployed in this office to study the use of energy flexibility, taking into consideration the comfort preferences of the occupants. Considering the conceptual model (Figure 3) this office concerns the Living Lab where the occupants are located. A floor plan of the office, which is usually used for meetings, is shown in Figure 15. Entering the office, is the sitting area, with a table and chairs. Opposite the door is the only wall of the room that faces the outside, it has four big double windows with blinds. Walking through the door on the left is the heat pump installed at a proper height. The mentioned heat pump is the only controllable device present in the considered office building, providing the energy flexibility required to implement DR methods. Other electrical devices (e.g. light bulbs) are also present in the office but do not provide energy flexibility as they are not controllable.

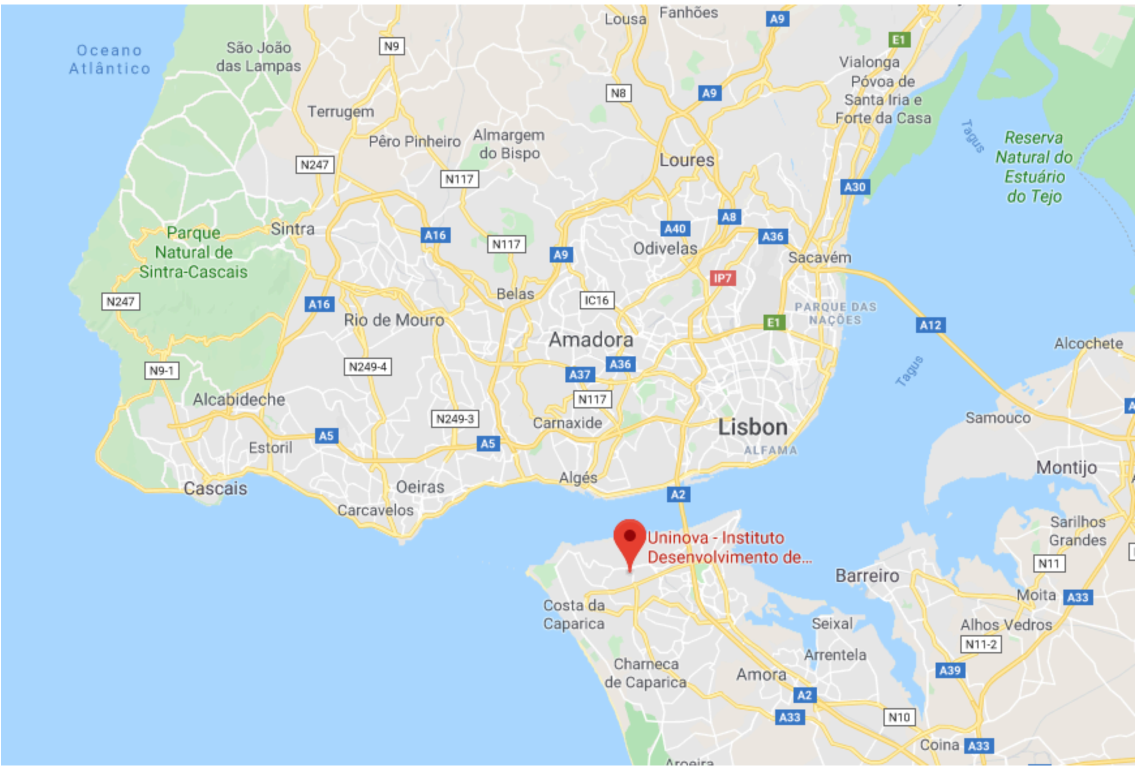


Figure 14 - Flex Lab location

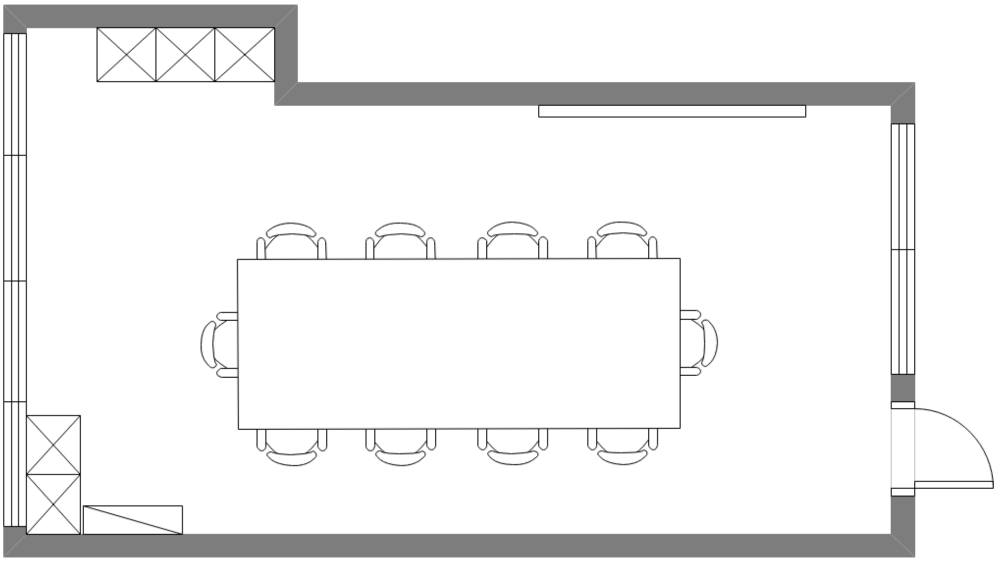


Figure 15 - Flex Lab

As described in the implementation, energy flexibility is achieved by deploying demand response algorithms in the RCU, which control the Living Lab's heat pump.

Energy flexibility is then used to change the operation of the heat pump, thus changing its typical consumption profile.

The DR algorithms are used to lower electricity costs considering tariffs in the Portuguese market. There are 3 different possible scenarios of the Portuguese tariff for energy prices; 1) simple tariff, where the price is constant not offering any change in the tariff throughout a day, 2) the Time-of-Use tariff with two periods (TOU_2) that shows two different prices for half-peak hours and off-peak hours and 3) the Time-of-Use tariff with three periods (TOU_3) where three tariffs are offered; half-peak hours, off-peak hours and peak hours. The different prices can be seen in the Table 6 (before taxes) [35] and in Figure 16 the different Portuguese tariffs are compared.

Table 6 - Portuguese Tariff

Transitional tariff for sale to end customers in normal low voltage		**Price**
Active Energy (>6,9kVA)		EUR/kWh
Flat tariff		0,1557
TOU_2	Half-peak	0,1890
	Normal off-peak	0,1025
TOU_3	Peak	0,2287
	Half-peak	0,1704
	Normal off-peak	0,1025

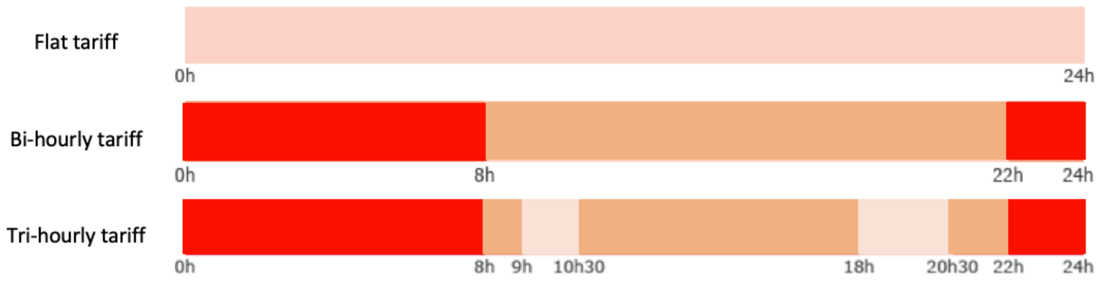


Figure 16 – Portuguese tariffs

From Figure 16 it is possible to see the distribution of the different periods of each tariff and identify that the off-peak hours of the bi-hour tariff and the tri-hour tariff are coincident.

In this case study, flexibility is only used when the heat pump is in the cooling phase. When the tariff is cheaper, the remote control unit puts the heat pump running at cooler temperatures and when it is more expensive the remote control unit puts the heat pump running at higher temperatures. By comparing the total heat pump operating time in the different operating scenarios, it is possible to calculate the total energy consumed, calculated from the instant the heat pump is turned on until the it is switched off. In this work, the Flex Lab system allows the user to know if using the energy flexibility of a controllable device, in this case a heat pump, can reduce electricity costs.

4.2 Scenarios

The following sections present the results of tests conducted at the Living Lab under real conditions. Two scenarios were considered to assess the impacts of using energy flexibility on electricity costs, the original scenario and the modified scenario. In the original scenario the energy flexibility provided by the heat pump is not used, and the device operates between a minimum and maximum temperature value according to the preferences set by the user. In the modified scenario, energy flexibility is used, keeping the temperature as high as possible during the most expensive periods and keeping the temperature as low as possible during the cheapest periods. Therefore, the Flex Lab allows to explore not only scenarios associated with the use of Energy Flexibility but also baseline scenarios that allow to study the normal operation of controllable devices. For each scenario, specific control algorithms that have been deployed in the remote control unit to control the heat pump are presented.

4.2.1 Original scenario

The purpose of the original scenario is to validate a second scenario in which energy flexibility is used. Thus, the algorithm only ensures that the controllable device has an operation that maintained the Living Lab at a comfortable temperature between 23 and 26 ° C.

It is important to note that the algorithm that allows this operation (i.e. control over the Living Lab's controllable devices) is implemented in the Remote Control Unit, as proposed in the conceptual model. The implemented control algorithm flowchart for the original scenario is presented in Figure 17.

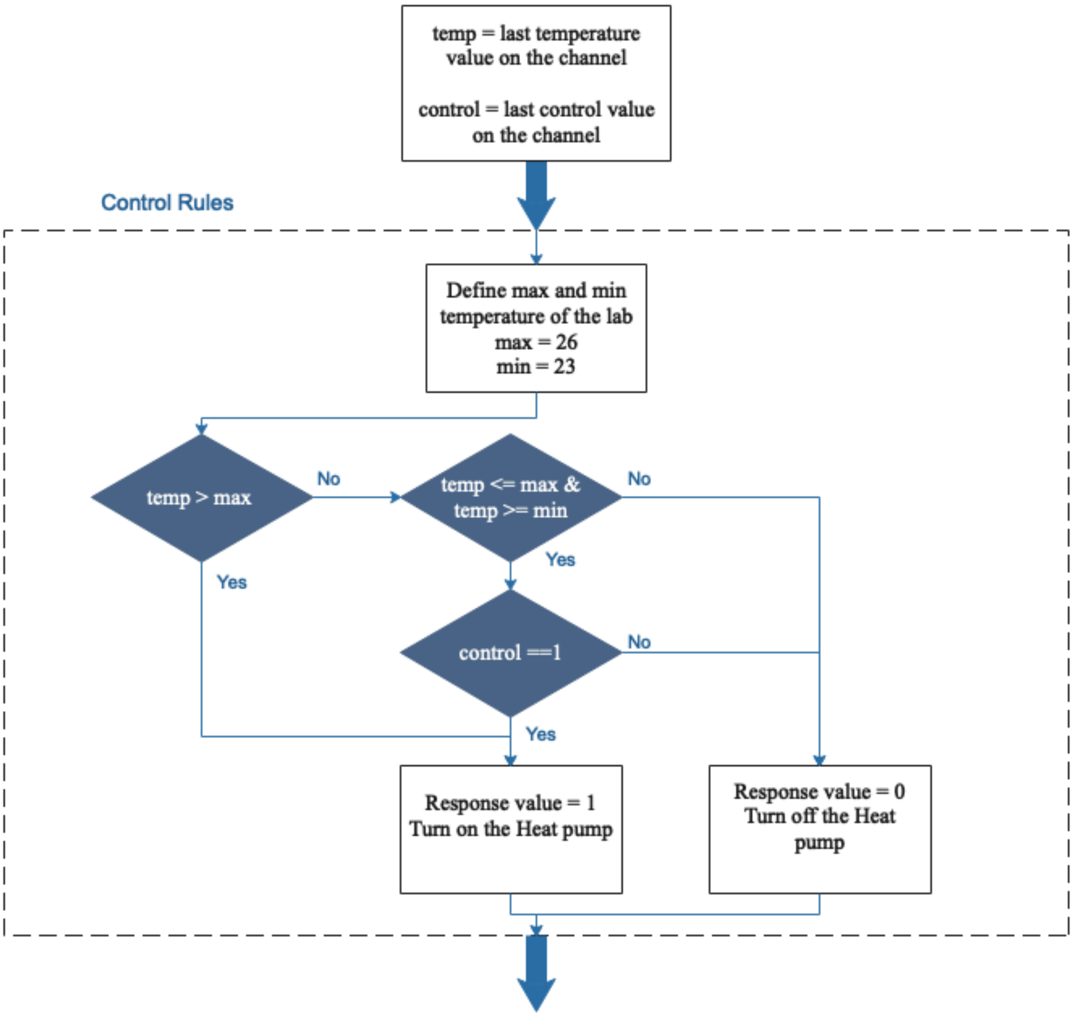


Figure 17 – Original scenario control algorithm block diagram

Operation of the remote control unit begins with fetching the last updated values of control of the heat pump and the Living Lab's indoor temperature from the interface. Having present the most recent information, the algorithm checks if the internal temperature of the Living Lab is between the range of temperatures chosen, between 23 and 26 ° C. When the internal temperature of the Flex Lab is above 26° C, the value 1 is sent to the control channel causing the actuator, controlling the heat pump, to act by turning it on. When the temperature is below 23° C, the value 0 is sent to the control channel causing the actuator to respond by turning off the device. When the temperature is within the stated range, the control algorithm first checks whether the last control value was 1 or 0 and maintains this value in order to continue the ongoing behavior, cooling or heating. Thus, the temperature in the Living Lab is maintained between 23 and 26 degrees Celsius as desired by the user.

4.2.2 Modified scenario

In the modified scenario, as mentioned in the conceptual model, energy flexibility is used by the applied demand response methods. The algorithm is implemented in the remote control unit to control the operation of the heat pump according to the electricity tariffs in Portugal. It was shown in table 6 that Portuguese tariffs offer two options for modified scenarios where the tariff changes: 1) the TOU_2, that shows two different prices for half-peak hours and off-peak hours and 2) the TOU_3 where 3 tariffs are offered; half-peak hours, off-peak hours and peak hours.

The DR algorithm implemented in the modified scenario sets higher temperatures for more expensive hours and lower temperatures for cheaper hours. It has been defined as a comfort preference for the heat pump to maintain the indoor temperature between 23 ° C 23.5 ° C during off-peak hours and between 25.5 ° C and 26 ° C during half-peak hours. Figure 20 shows a flowchart that describes the modified scenario algorithm implemented. Considering Figure 16, the half-peak hours and off-peak hours of the TOU_3 correspond to those of the TOU_2, thus the same DR algorithm, described in Figure 18, was implemented for both cases.

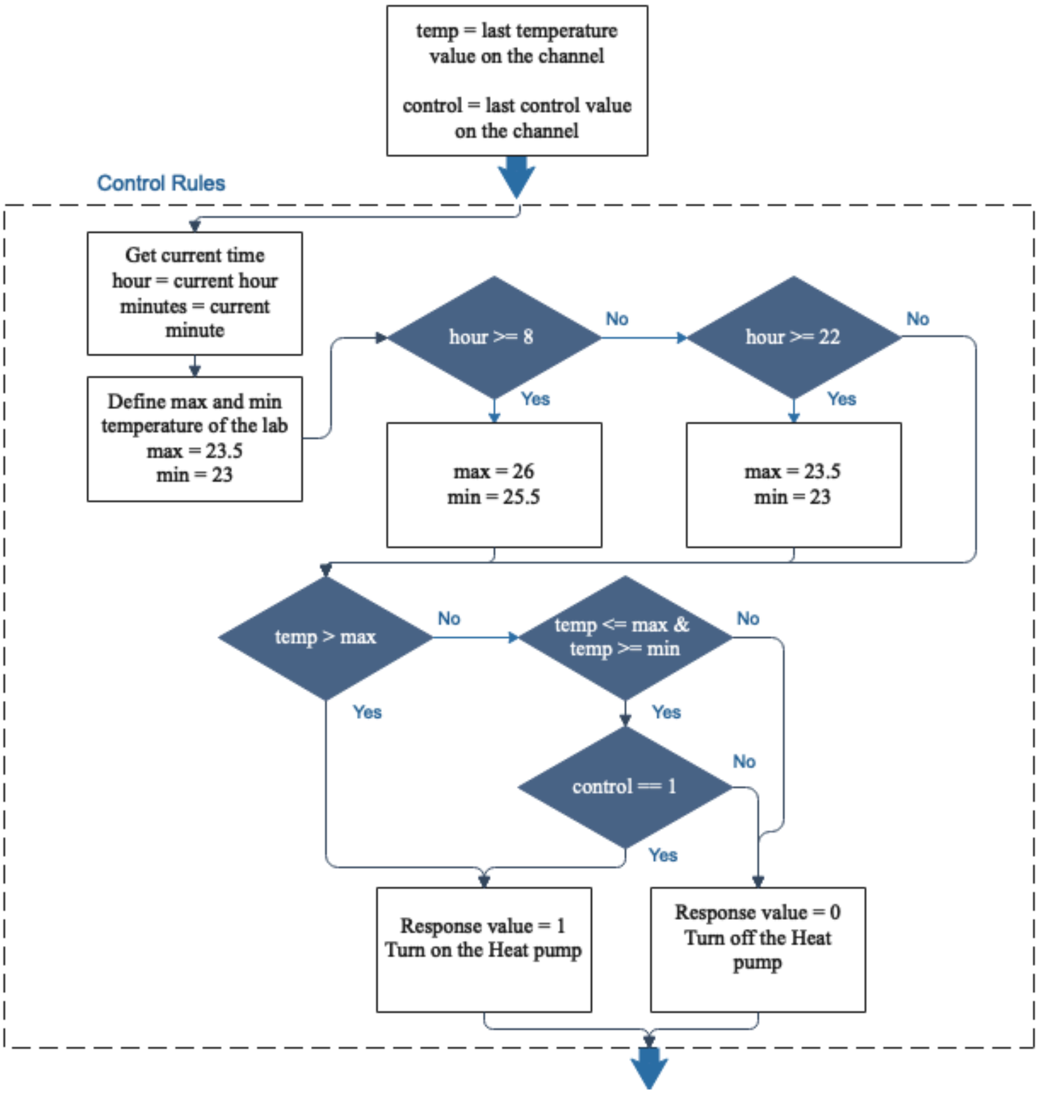


Figure 18 - Modified scenario control rules block diagram

As in the original scenario, the Remote Control Unit first fetches the latest Living Lab's indoor temperature and control values present in the interface. Because tariffs change over time, the controller gets the current time, hours and minutes, and sees which temperature range to apply. If time is within off-peak hours, the heat pump should maintain the indoor temperature between 23 and 23.5 ° C. If the time is within half-peak hours then the heat pump should maintain the room temperature between 25.5 ° C and 26 ° C. Having the temperature range defined in the RCU, the rules used to control the heat pump behavior for the modified scenario are similar to the ones applied to the original scenario. When the indoor temperature of the Living Lab is above maximum temperature, the value 1 is sent to the control channel. When the temperature is below minimum temperature, the value 0 is sent to the control channel to turn off the heat pump. When the temperature is between the maximum and minimum temperatures, the control rules check if the last control value was 1 or 0 and maintains that value in order to continue the ongoing behavior (i.e. continuing cooling the room or waiting for the indoor temperature to reach the maximum temperature defined). In Figure is possible to see an example of the modified scenario algorithm applied to a temperature sensor.

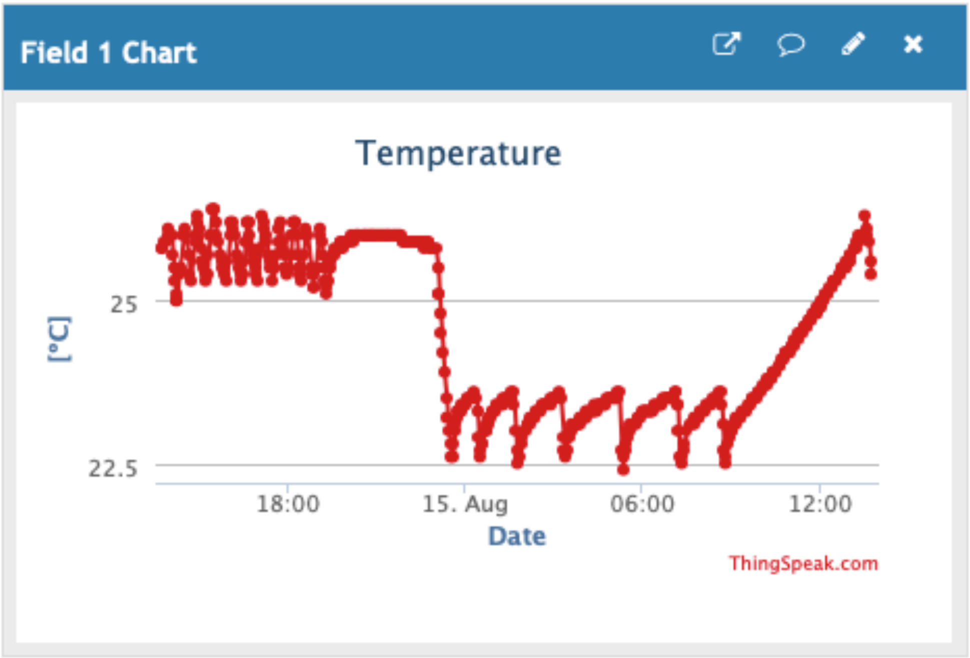


Figure 19 - Sensor's virtual representation with modified scenario control algorithm

In Figure 19 is an example collected from the interface of the temperature sensor virtual representation, the temperature sensor collects the indoor temperature of the living lab. According to the implemented algorithm, during half-peak hours the temperature stays between 25.5 ° C and 26 ° C and during off-peak hours between 23 ° C and 23.5 ° C.

4.3 Results and Analysis

The results of the tests performed considering the case study introduced in Section 4.2 are presented in this section. Considering the Living Lab referred in the conceptual model, the results of the experiment were collected at the office mentioned in the implementation. Also, the DR algorithms described in the case study were implemented in the remote control unit to control the Living Lab’s heat pump. Regarding the data analyzed to obtain the results, data of a total of 17 days of August 2019, were collected from the data storage module to conduct the experiment.

In order to compare the results obtained in the two scenarios, it was necessary to find two days that had similar outdoor conditions. In this case temperature was chosen to perform the comparison. For the analyses of selected days, all the possible combinations of days from both scenarios were considered. From the 17 days collected, 5 were associated to the original scenario and the other 12 to the modified scenario, with a total of 60 combinations. The mean square error between the outdoor temperature profiles of each combination was used to assess the similarity of outdoor conditions (figure 20).

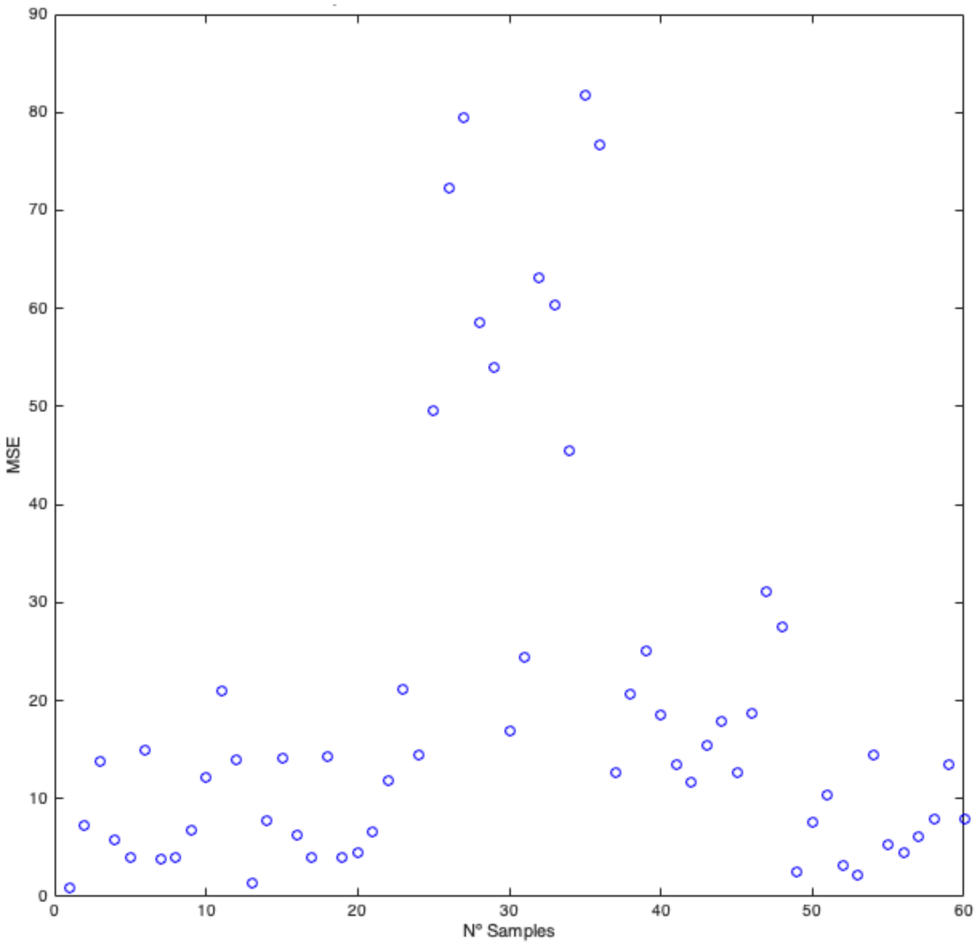


Figure 20 - Mean squared error between the outdoor temperature profiles of each combination

Based on the results shown in figure 20, the pair of days with a smaller mean squared error was the 1st of August and 13th of August, with a mean squared error of 0.9724. The smaller the mean squared error, the more similar the outdoor temperature profiles of the days are. In order to pick the best pairs for each day of the original scenario, the day closest to the outdoor temperature of the modified scenario was chosen, more precisely, the pairs with the lowest mean square error. The resulting pairs were: I)1Aug – 13Aug; II)2Aug – 13Aug; III)27Aug – 17Aug; IV)26Aug – 18Aug; V)8Aug – 18Aug; in which the first day of the pair is the original scenario day and the second one the modified scenario day. Subsequently, for each pair the heat pump run times, energy consumption and associated costs were calculated.

To calculate the run time, the amount of time the heat pump was turned on was considered. Furthermore, for the Original scenario days, the flat tariff was applied with a price of 0,1559€/kWh and for the modified scenario the TOU_2 tariff was considered with the tariff value of 0.1025€/kWh for off-peak hours and 0.1819 €/kWh at half-peak times. The results of heat pump run times, energy consumption and costs calculated for each pair, can be seen in table 7.

Table 7 - Comparison of original scenario days and modified scenario days

Pair	MSE	Run time [H]	Off-peak energy consumption [kWh]	Half-peak energy consumption [kWh]	Total energy consumption [kWh]	Off-peak Cost [€]	Half-peak Cost [€]	Total cost [€]	Savings [%]
V	16.846	1.94	-	-	5.44	-	-	0.848	-56.6
		2.95	2.18	6.07	8.25	0.224	1.104	1.328	

Original scenario
Modified scenario

In Table 7, pairs were ordered in ascending order of mean square error, leaving the most similar profiles at the beginning. It can be seen from Table 7 that the modified scenario days have a shorter run time except for an exception, resulting in lower total energy consumptions and consequently cost savings. It was possible to see positive savings even knowing modified scenario days have higher prices. To understand better the results presented in Table 7, the outdoor temperatures for each pair were compared, in Figure 21 the first pair is illustrated.

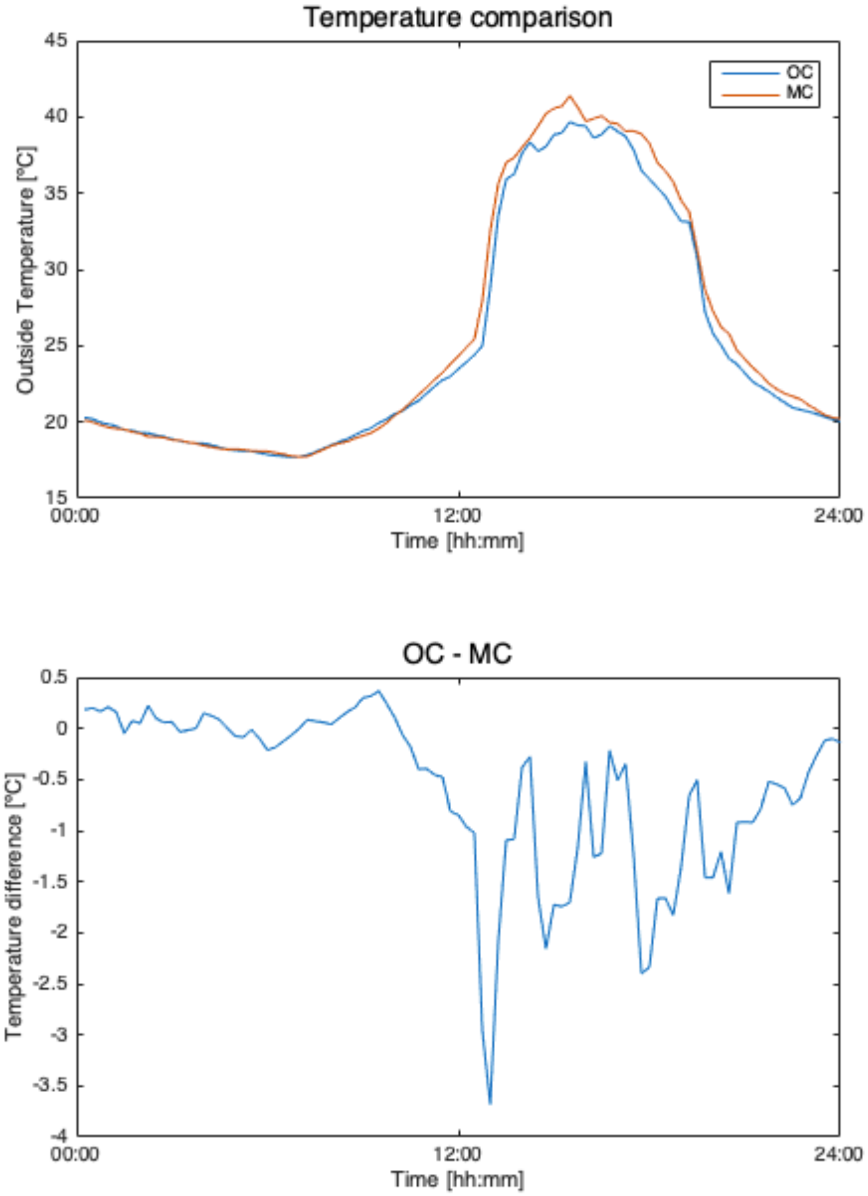


Figure 21 - Pair I) Aug and 13 Aug

In Figure 21, pair I is analyzed showing in the first graph the external temperatures of the two days and in the second graph the temperature difference (temperature from the original scenario day minus the temperature from the modified scenario day). The modified scenario day is represented in orange and the original scenario day is represented in blue. It is possible to observe that the day corresponding to the modified scenario was generally warmer and the temperature increase occurred earlier than the temperature increase verified in the original scenario day. Since the modified scenario day was warmer we can assume that the heat pump had to work longer. On the other hand, it is possible to confirm from the table that the run time of that day was smaller than the day of the original scenario, meaning the rules applied to the RCU reduced the heat pump operation time. Similarly, because the temperature increase occurred earlier than the temperature increase verified in the original scenario day we can conclude that the heat pump also had to start working earlier than the original scenario day. Hence, as the heat pump operation was more exhaustive on the day of the modified scenario we can assume that the results presented in Table 7 for the comparison of pair I are actually better than they appear to be. This means that if the temperature conditions were the same, the heat pump would have bigger savings and the results would have been better. To better understand the results of Table 7, all variables of the Living Lab were analyzed. First, the results of 01/08/2019, where the original scenario was applied, are presented in Figure 22.

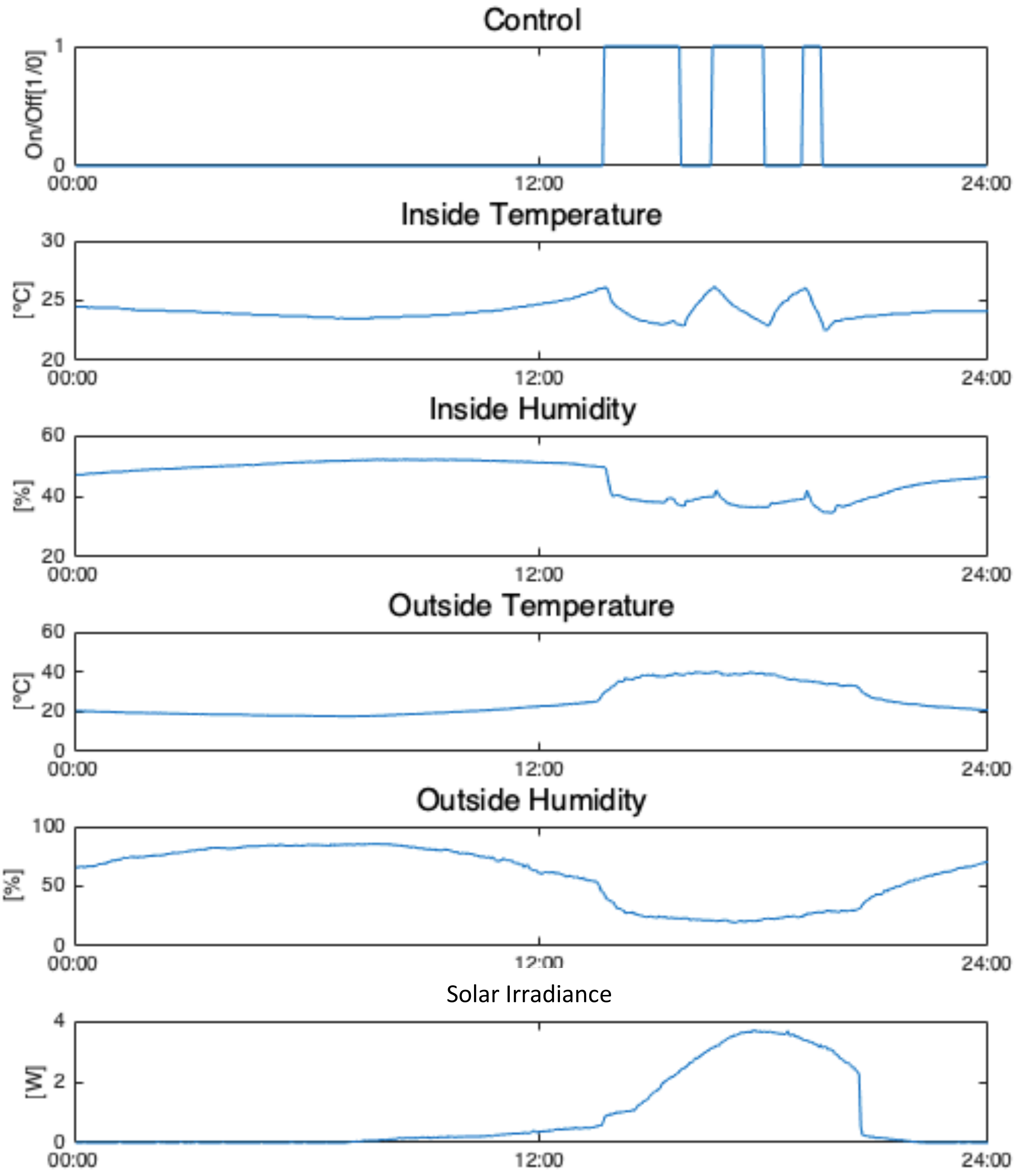


Figure 22 - Day 01/08/2019 results with the original scenario

Figure 22 gathers all Living Lab's collected variables on a day the original scenario was considered. It is possible to see that the demand response algorithms applied to the RCU (Figure 17), maintained the temperature of the room between 23ºC and 26ºC as the supposed given the implementation. The first plot is the result of the actuation installation (Figure 10), the next two plots present the indoor conditions of the Flex lab, collected from the installation shown in Figure 8, and the last three show the outdoor conditions of the Flex Lab, collected from the installation represented in Figure 6.

In the first graph is the information regarding the heat pump control, that resulted of the RCU analyses of the room conditions, which was retrieved from the control channel information available in the data storage module. When the value is 1 the heat pump is on and accordingly when it is 0 the pump is off, as mentioned in the implementation. It is possible to observe that during this day the heat pump only worked during the afternoon, after 12:00.

The second graph shows the indoor temperature of the Living Lab that remained between 23 and 26 degrees Celsius, therefore respecting the desired conditions. It is possible to see that when the heat pump is on (control value is 1) the indoor temperature of the Living Lab decreases and when the heat pump is off (control value is 0) the indoor temperature of the Living Lab increases. Indoor humidity shows an opposite behavior to indoor temperature, however the increase in indoor humidity is significantly slower than that shown by indoor temperature.

As can be observed from the outdoor temperature of the Living Lab it reached a maximum temperature of 39.68ºC and a minimum temperature of 17.7ºC. When outdoor temperature is low, outdoor humidity is high reaching a maximum of almost 90%, but when outdoor temperature increases, humidity levels decrease showing that they have opposite behaviors. It is possible to see the cause effect between the output of the photovoltaic cell, outdoor temperature and outdoor humidity. When the output of the photovoltaic cell increases, the outdoor temperature increases as well while the humidity decreases. On the other hand, when the output of the photovoltaic cell decreases the opposite occurs. To better understand the relation between the Living Lab’s location and its sun exposure and its consequent effects on the output of the photovoltaic cell results, Figure 23 shows the movement of the sun in relation to the positioning of the Living Lab and the output of the photovoltaic cell.

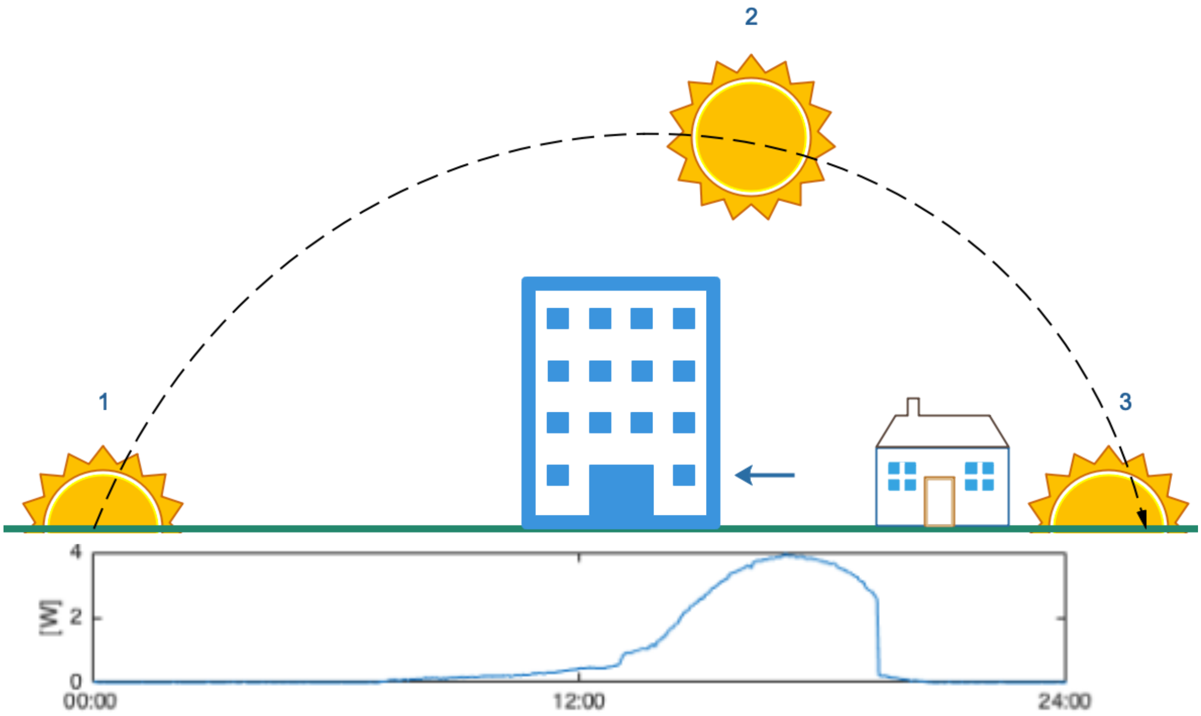


Figure 23 - Living Lab solar exposition

The Living Lab is located on the ground floor of a building marked with an arrow in Figure 23, which is also where the photovoltaic cell is positioned outside the Living Lab's window. Three important moments that explain the mentioned relation were identified and marked in the figure with numbers. In the first moment, the sun rises on the back of the building, opposite to where the Living Lab is located, agreeing with the photovoltaic cell output that shows low diffuse radiation values because the Living lab is not yet exposed to direct solar radiation. At noon, the sun is at its highest altitude above the building and the Living Lab which starts to get some diffuse radiation. After noon, moment 2, the sun is located in front of the Living Lab until it hides behind the building in front of the Living Lab (moment 3), as can be seen from the output of the photovoltaic cell that no longer receives radiation. It is possible to conclude that when the living lab window is more exposed to solar radiation, i.e. when the output of the photovoltaic cell has higher values, it is when the interior temperature of the living lab has higher values.

The results from day 13/08/2019 (modified scenario) are presented in Figure 24.

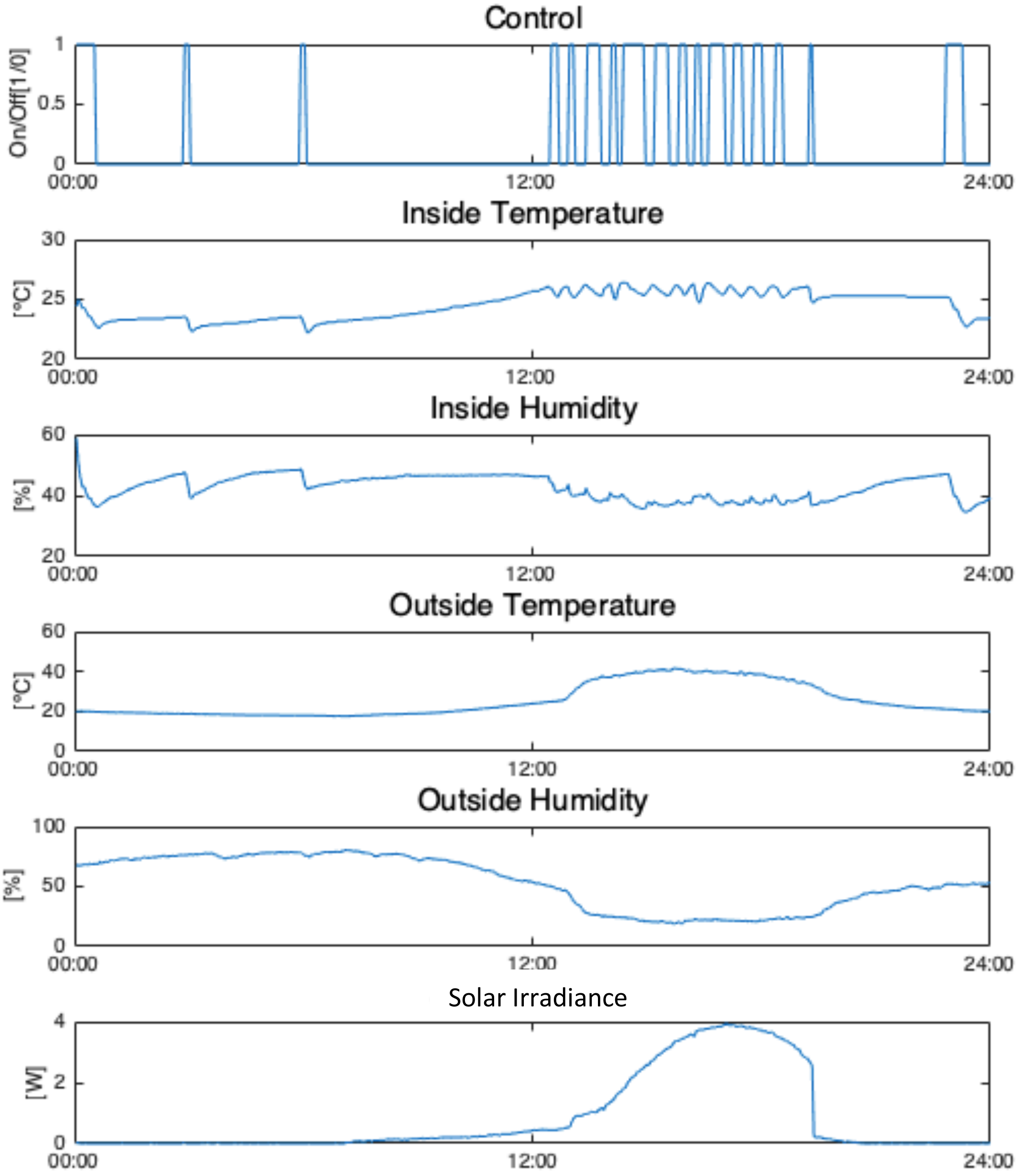


Figure 24 - Day 13/08/2019 results with the modified scenario

Figure 24 shows all Living Lab collected variables on the day the modified scenario was considered. Like in the previous scenario, it can be observed that the demand response algorithms deployed in the RCU (Figure 18), maintains the indoor temperature of the room between 23 ° C and 23.5 ° C (during off-peak hours) and between 25.5 ° C and 26 ° C (during off-peak hours). In the modified scenario, when the heat pump is on, the indoor temperature and humidity of the Living Lab decrease as it was seen for the original scenario, and when the heat pump is off the indoor temperature and humidity increase. In this case it is also possible to observe that the heat pump operation was distributed throughout the day and was not restricted to the afternoon as shown in the original scenario (Figure 22). Indoor humidity shows an opposite behavior to indoor temperature, however the increase in indoor humidity is significantly slower than that shown by indoor temperature. As can be observed from the outdoor temperature of the Living Lab it reached a maximum temperature above 40ºC and a minimum temperature of 17.72ºC. After comparing both days variables from pair I, it is possible to verify that the outdoor temperature conditions are very similar between both chosen days even though the modified scenario day was warmer. The outdoor humidity and output of the photovoltaic cell show similar profiles to the original scenario day, although output of the photovoltaic cell shows higher value on the modified scenario day.

After a close analysis of the control actions from the two days (pair I) it is possible to observe that in the original scenario the heat pump was switched on only three times during the afternoon but for a long period. On the other hand, in the modified scenario the heat pump was turned on more frequently during the whole day but for shorter periods. The outdoor conditions of the modified scenario turned out to be warmer than the original scenario, noting that if the day had been colder, the savings presented in Table 7 would have been greater.

To understand why the results of pair II resulted in negative savings, external temperatures were analyzed in Figure 25.

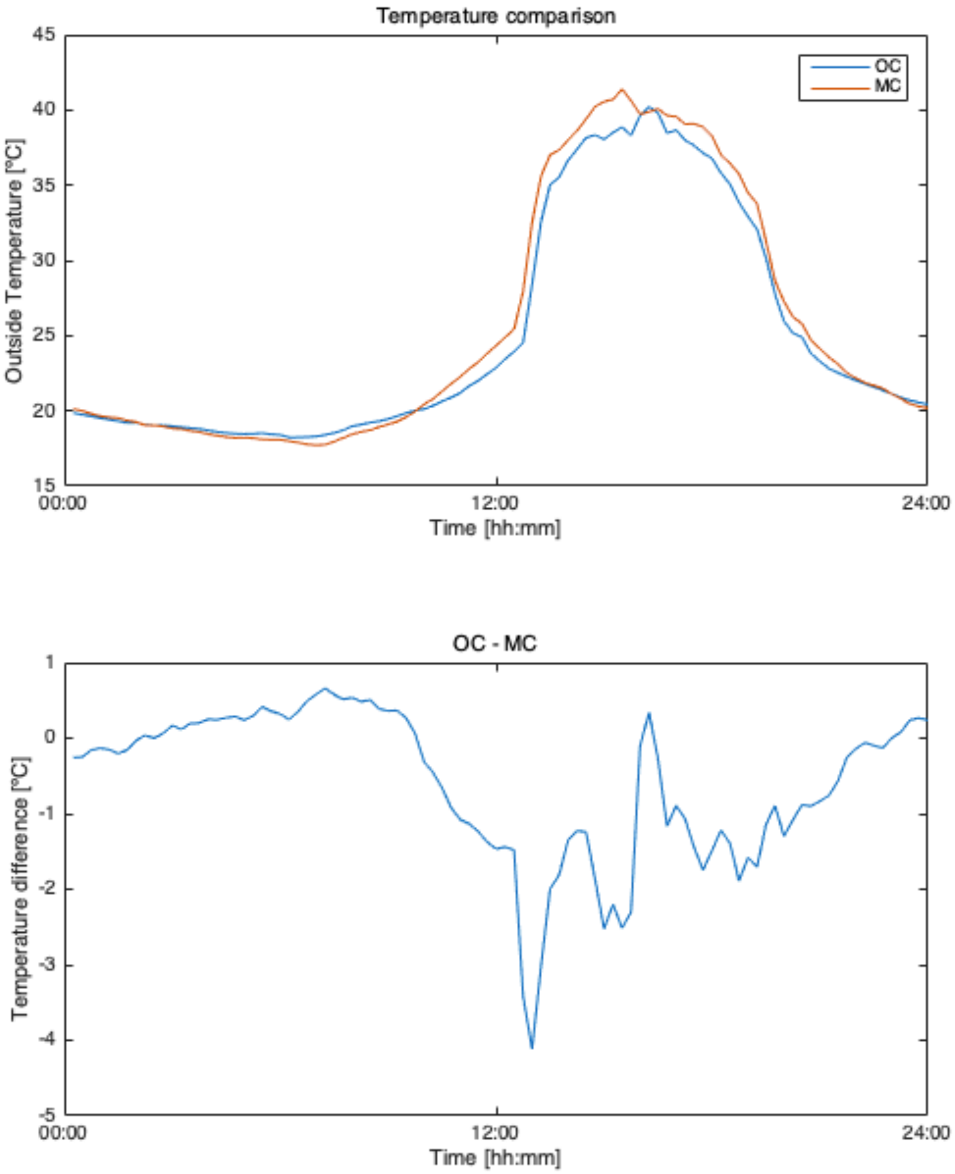
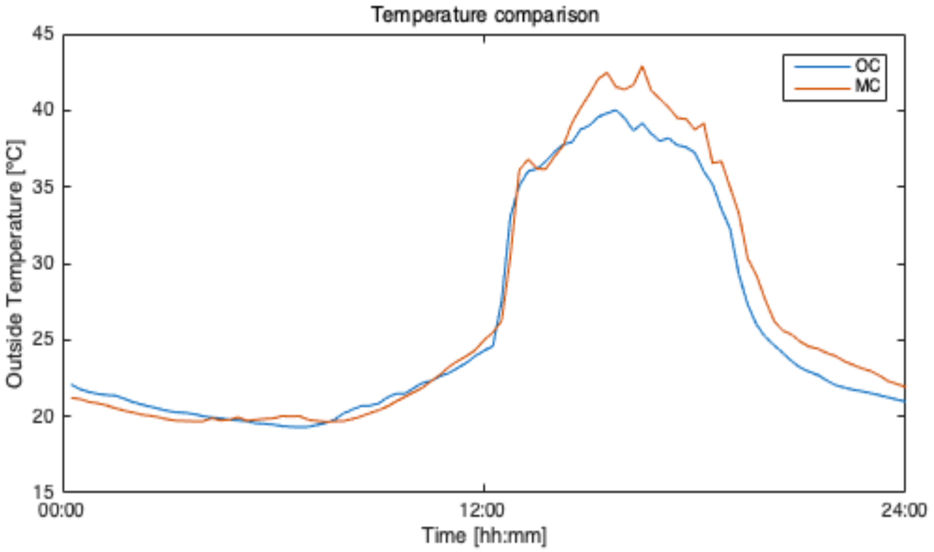


Figure 25 - Pair II) 2 Aug and 13 Aug

In Figure 25 pair II is analyzed, showing in the first graph the external temperatures of the two days and in the second graph the temperature difference of the two days. The modified scenario day is represented in orange and the original scenario day is represented in blue. It is possible to observe that the day corresponding to the modified scenario was generally warmer and the temperature increase occurred earlier than in the original scenario day. Since the modified scenario day was warmer we can suppose the heat pump had to work longer than the original scenario day. Also, because the temperature increase occurred earlier in the modified scenario day (Pair II), it is possible to suppose that the heat pump had to start working earlier resulting in even longer run time. Still, it can be confirmed in Table 7 that the run time of the modified scenario day was lower than the day of the original scenario similarly to what was analyzed in Pair I.

When comparing the run time of Pair II, it is possible to see that it was almost the same, 2.98 (Modified Scenario) and 3.05 (Original Scenario). In this case it is possible to conclude that because the day was significantly warmer, it made the pump work as much as the day the original scenario was applied instead of less as predicted if the days were similar. For these reasons in the end the savings were negative as the tariff applied to the modified scenario has higher prices.

Next, pair III was analyzed which even though showed in Table 7 a similar run time for both days, had positive savings.



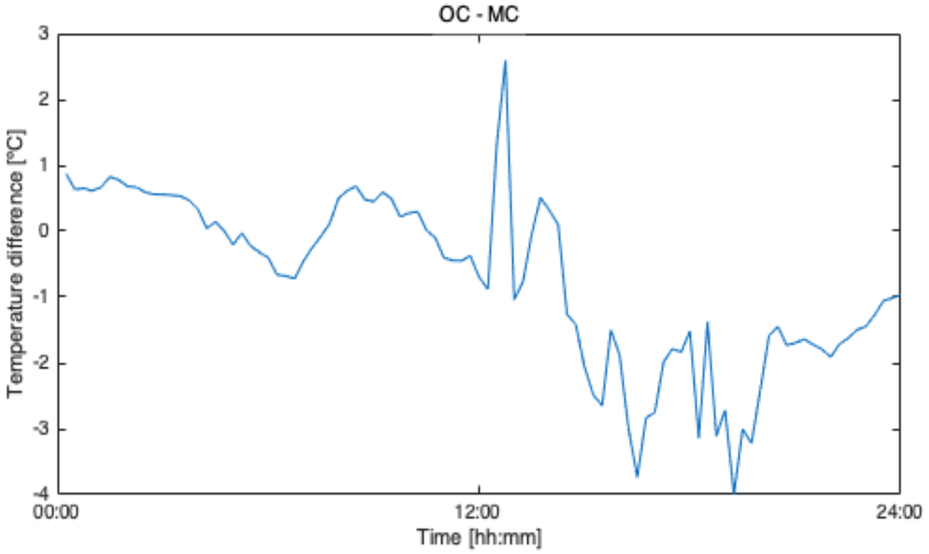


Figure 26 - Pair III) 27 Aug and 17 Aug

In Figure 26 pair III is analyzed, showing in the first graph the external temperatures of the two days and in the second graph the temperature difference of the two days. The modified scenario day is represented in orange and the original scenario day is represented in blue. It is possible to observe that the day corresponding to the modified scenario was generally warmer but this time the temperature increase occurred simultaneously in both scenarios. In Table 7, when comparing the run time of the day the modified scenario was considered with the day of the original scenario, we can see that it was almost the same, 3.81 and 4.13 respectively.

To try and reduce costs one off the approaches was operating the heat pump at a higher temperature range during half-peak hours and lower at off-peak hours. Since the temperature stays lower during the off-peak hours it will take longer for the inside temperature to reach the maximum temperature when changes to half-peak hours. This would delay the start of the pump's operation at half-peak hours and distribute it by the off-peak hours. From pair III it is possible to understand if the rationale behind the idea of choosing a high range of temperatures for half-peak hours and a low range for off half-peak hours has any impact in costs. In the plot showing the temperature difference (Figure 26), it is possible to verify a small difference in outdoor temperature when the temperature increase occurs, supporting the idea that both days warmed up simultaneously.

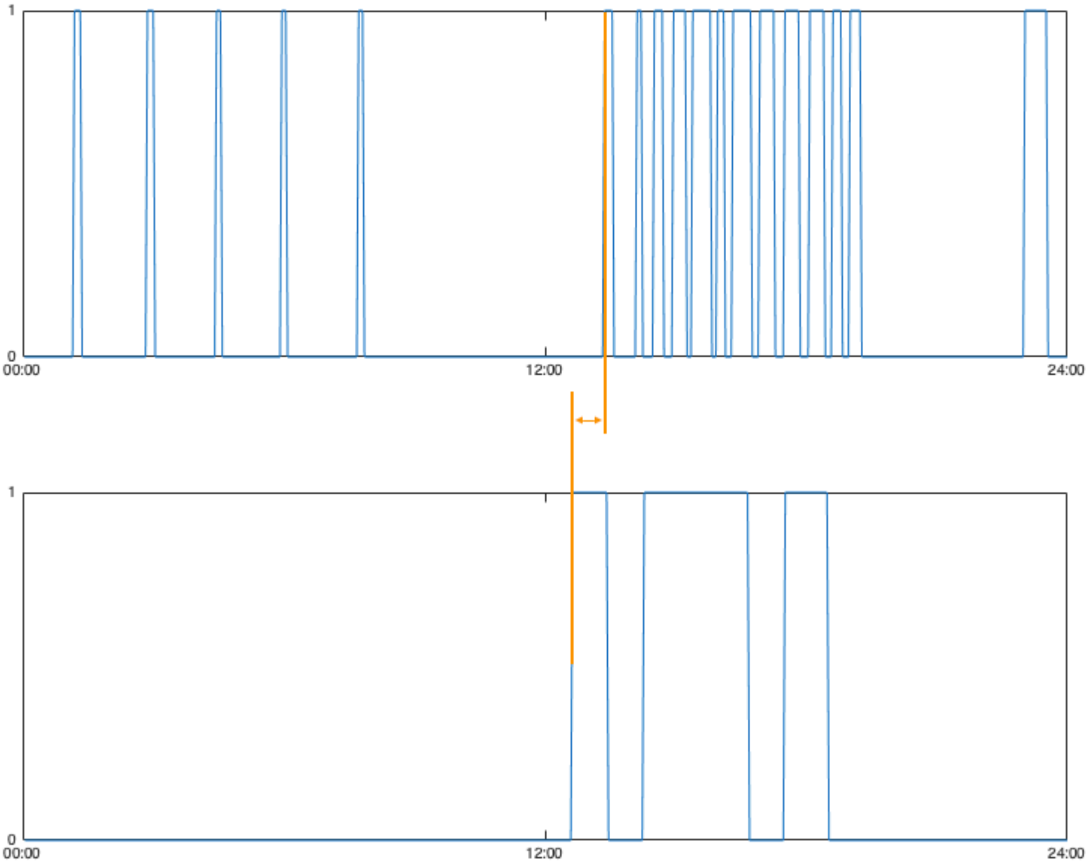


Figure 27 – Control from pair 27 Aug and 17 Aug

In Figure 27 it is possible to see the operation of the heat pump, above in the modified scenario, and below in the original. From the analyses of both profiles it is possible to see that the heat pump in fact started working latter in the modified scenario, consequently taking longer to achieve the max temperature of the indoor of the flex lab and delaying the beginning of the heat pump operation during half-peak hours.

The pair IV showed positive savings in Table 7. Bellow both outside temperatures and their difference are presented.

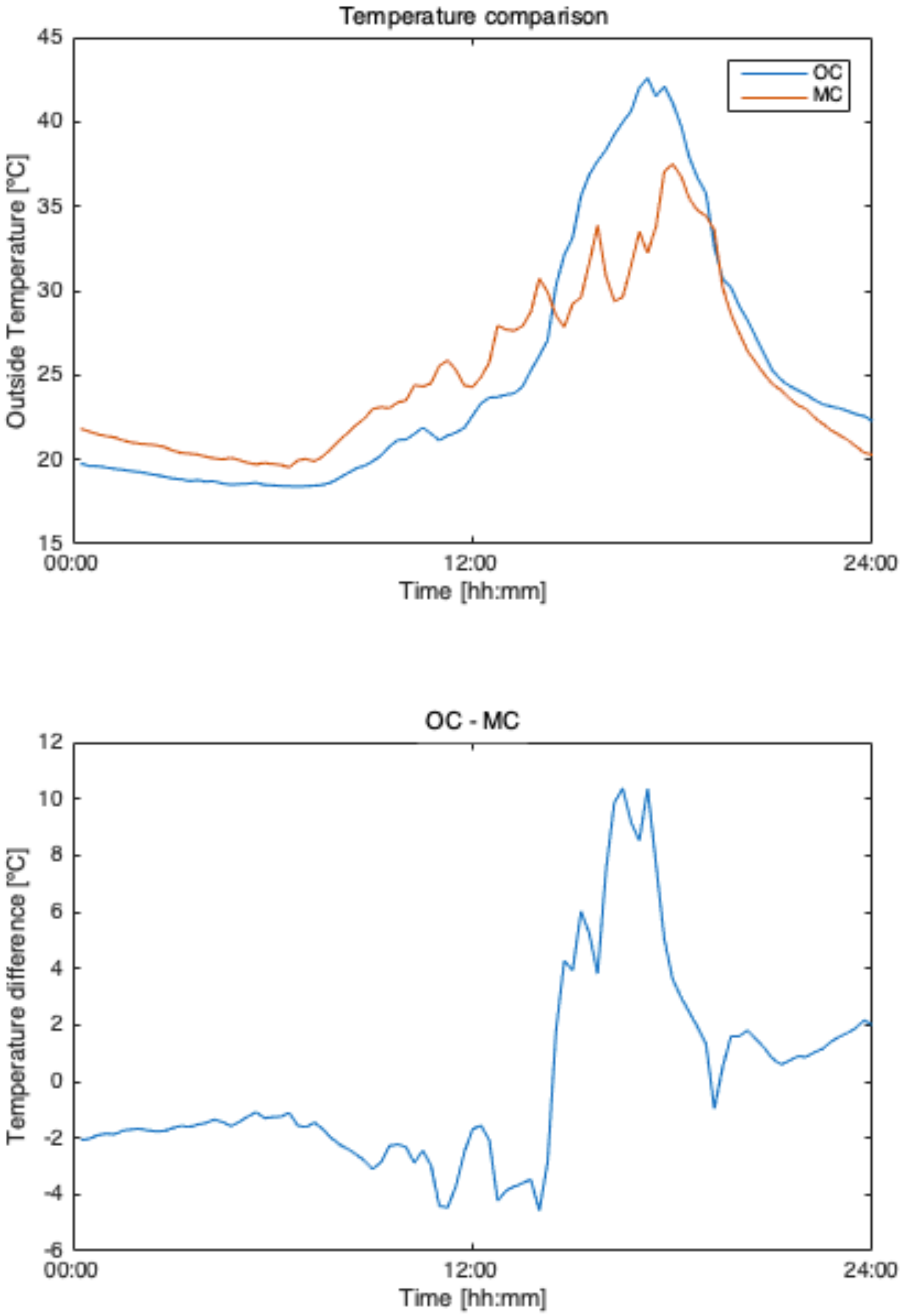


Figure 28 - Pair IV) 26 Aug and 18 Aug

Figure 28 concerns the external temperatures and the temperature difference of the Pair IV. As expected, is possible to see that the pair has very different temperature profiles since the high mean square error of the pair is high (11.746). Still, comparing both profiles it is possible to see that the original day was warmer than the modified scenario. From Table 7 it is possible to see that the run time was higher in the original scenario than in the modified scenario and therefore consumption was higher in the original scenario, explaining why the savings were positive.

The last and most different pair V has a mean square error of 16.846, and savings of -56.6%.

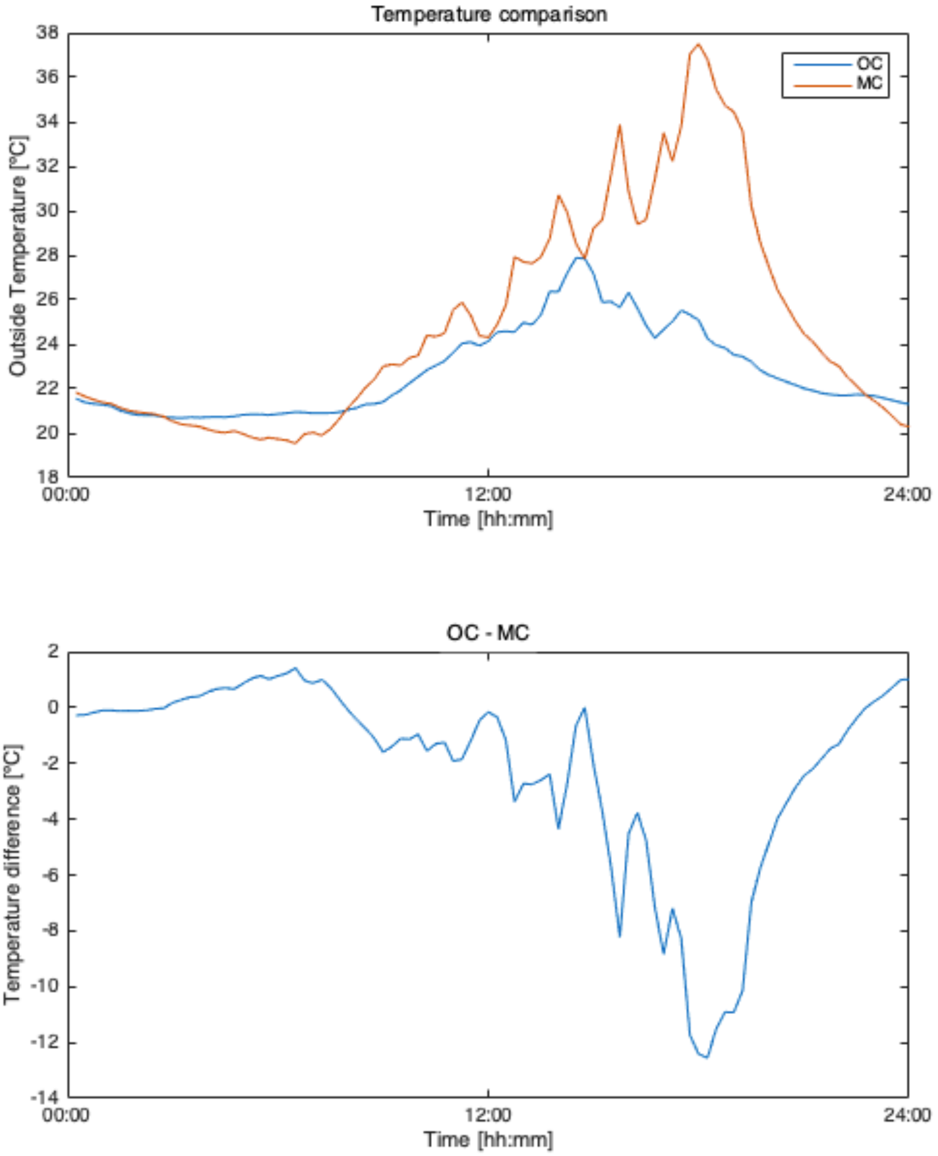


Figure 29 – Pair V) 8 Aug and 18 Aug

Figure 29 concerns pair V, showing in the first graph the external temperatures and in the second graph the temperature difference of the two days of the pair. This pair has the most different temperature profiles from all the pairs analyzed with a mean square error of 16.846. In this case the modified scenario shows warmer temperatures during almost the whole day. From Table 7 it is possible to see that the run time was bigger in the modified scenario and explaining why there was no positive result.

To explore the benefits of the control rules created in the modified and study if they have any real impact in costs, the same pairs were compared but this time applying the same tariff (TOU_2). This was is possible to see the savings results by only changing the heat pump consumption profile while maintaining the tariff. The Table 8 shows the same pairs, analyzed with the TOU_2.

Table 8 - Comparison of both case scenario days applying TOU_2

Day Aug	MSE	Run time [H]	Off-peak energy consumption [kWh]	Peak energy consumption [kWh]	Total energy consumption [kWh]	Off-peak Cost [€]	Peak Cost [€]	Total cost [€]	Savings [%]
1	0.9724	3.66	-	3.66	10.25	-	1.864	1.864	26.9
13		2.98	1.96	6.38	8.34	0.201	1.161	1.362	
2	1.3125	3.05	-	3.05	8.53	-	1.552	1.552	12.2
13		2.98	1.96	6.38	8.34	0.201	1.161	1.362	
27	2.1796	4.13	-	4.13	11.57	-	2.104	2.104	18.0
17		3.81	2.73	7.95	10.68	0.279	1.447	1.726	
26	11.746	3.78	-	3.78	10.58	-	1.924	1.924	31.0
18		2.95	2.18	6.07	8.25	0.224	1.104	1.328	
8	16.846	1.94	-	1.94	5.44	-	0.989	0.989	-34.3
18		2.95	2.18	6.07	8.25	0.224	1.104	1.328	

From Table 8 it is possible to see that the heat pump only works during half-peak hours and by applying DR rules and changing the range of temperatures during the half-peak and off half-peak hours have positive savings. The modified scenario rules help spread the operation of the heat pump to off-peak hours and guarantee that it will take longer for the heat pump to start working during half-peak hours by changing the temperature from a lower temperature during off half-peak times to higher temperature during half-peak times.

5 Conclusion and Future Work

This chapter begins with the presentation of a general synthesis of the work developed, as well as the main contributions of the research carried out and their conclusions. Future work is presented in Section 5.2 that will lead to possible improvements in the work developed.

5.1 Conclusions

The energy sector is currently a major contributor to greenhouse gas emissions due to the use of fossil fuel-based energy sources. Thus, the importance of seeking sustainable energy solutions, in order to reduce the impact that energy production has on environmental pollution, capable of meeting energy needs. The introduction of renewable sources into the electricity grid is part of a possible solution to reduce the use of fossil fuel based resources. However, due to the characteristic variable production profile of these sources, it is sometimes necessary to resort to sources based on fossil fuels as a way to solve the imbalances caused by the system's production-consumption relationship. Because buildings take part of total final energy consumption, this emphasizes the importance of why it is important to research energy consumption in buildings. Thus, it is necessary to find a solution that meets the requirements mentioned above and that has a positive impact on the network. Following this, a system in which the user has the central role to remotely apply demand response methods to office buildings using existing energy flexibility given by controllable devices and using a Living Lab approach could be an integral part of a possible solution. This could be part of a solution to the problems of the grid caused by the unstable production pattern of renewable sources, reducing the need to use fossil fuel-based power sources so often to solve these problems. However, in order to be able to use the energy flexibility provided by the controllable devices, in this case the heat pump, considering the comfort levels of the occupant of the living lab, it is necessary to have the ability to monitor the living lab conditions and control the controllable device. Thus, in the present work a system was developed in which the user has the central role to remotely apply demand response methods to a heat pump using existing energy flexibility given by it and using a Living Lab approach.

The selected approach uses energy flexibility on the principle of changing the operation of the heat pump by changing its state from on to off. Changing the operation of the heat pump changes the heat pump energy consumption profile. In this case, energy flexibility is obtained by deploying demand response algorithms to the RCU, that control the Living Lab heat pump, to lower electricity costs considering tariffs in the Portuguese market. When the tariff is off-peak, the remote control unit puts the heat pump working in lower temperatures and when is half-peak tariff the remote control unit puts the heat pump working at higher temperatures. When comparing the heat pump run times in the different operating scenarios, it is possible to calculate the total energy consumed from the instant the heat pump is turned on until the it is turned off.

Through the various tests performed it was possible to validate the operation of the system, analyze in detail the use of energy flexibility and its influence on electricity costs. It was also observed in the various tests the influence of direct solar exposure of the sensors placed outside the Living Lab, leading to the outdoor temperatures collected being higher than the actual values. Due to lack of time, the boxes were not developed as expected at the end of the work. As tests were conducted in real environment conditions, the selection of days was very important for the analysis of results. Two scenarios where applied with a total of 59 combinations of days to be compared. Each combination has a scenario where energy flexibility was not used and another where energy flexibility is used. Of the 59 combinations, the 5 with the most similar profiles, smaller Mean Square Error, were chosen for analysis.

With the demand response algorithms applied in the RCU, it is possible to reduce the final consumption, by placing a higher temperature range at half-peak hours and a lower temperature range at off-peak hours, in two ways; since the temperature is lower during the off-peak hours it will take longer to reach the new maximum temperature, during half-peak hours, and start the pump (Figure 30); according to the thermodynamic model presented there are less losses since the energy used by the controllable devices is lower.

Comparing a scenario where energy flexibility is not used, with one where energy flexibility was used and a variable tariff was applied, it was possible to see a change in energy consumption and savings. In the event that a variable tariff is applied to scenarios with and without energy flexibility, there is a significant difference in consumption and savings. That is, the more days are taken the larger the number of samples and the DR algorithm can be optimized and costs reduced. It is important to note that the remote control can be done through the proposed model in which the remote control unit is independent of the living lab, enabling the remote sharing of living lab resources. Finally, the Flex Lab achieved significant savings from electric conditioning of the controllable device, using the energy flexibility available, without sacrificing the comfort of the users.

5.2 Future work

The case study results reported in this research work are indicative of the Flex Lab performance under realistic conditions. Furthermore, the data were collected during the warmest month of the year (August), on different days for each case study. For more beneficial analyses, extensive simulations should be performed simultaneously, with the same weather conditions and for at least one year, for both case scenarios. An actual comparison of the two scenarios, would bring more accurate results. Also, the controller only allowed the heat pump to work in cooling mode which could be adapted to work in both modes in future work.

For the study of the heat pump a mathematical model that describes its behavior was not considered. In future work, it would be interesting to study a model that encompasses the operation of the heat pump and the temperature of the living lab.

To apply the Flex Lab model in a real scenario, real installations were implemented, however, in the developed system the sensors responsible for the collection of the living lab's external conditions were exposed to direct solar radiation, resulting in higher outside temperatures than those experienced. Thus, in future work the sensors referred to, should be placed in the shade without being directly exposed to solar radiation.

Finally, it is important to mention that although the Flex Lab use of flexibility, by applying demand response algorithms in office buildings, resulted in cost savings, few samples have been analyzed. Just as a model predictive control was not created to estimate and optimize pump operation, thus it would be interesting to develop this model and compare it with the samples taken and presented in this thesis.

6 Bibliography

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