João Miguel Reis Araújo Proença Cambeiro

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The Human in the loop in Cyber-Physical Systems: the case of Building Automation

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Adviser: Vasco Miguel Moreira do Amaral,
Assistant Professor, NOVA University of Lisbon

Examination Committee

Chairperson:	Henrique João Lopes Domingos
Raporteur:	Paulo Jorge Fernandes Carreira
Member:	Vasco Miguel Moreira do Amaral

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ABSTRACT

Context: The world is facing environmental challenges due to carbon dioxide emissions. Building energy consumption accounts for thirty to forty-five per cent of global energy consumption. Changing these figures is imperative for achieving environmental sustainability. Building Automation Systems (BAS) can be considered a type of Cyber-Physical Systems (CPS) that have the objective of increasing energy efficiency while maximising human comfort.

Problem: Automated systems usually do not consider human effective participation as a tool that can be used to achieve the system's goals

Solution: Humans can assume several roles in the available building automation control loops. Building operators determine operating rules; building users can be the source of data used for automated decisions and also the system may require their actions to change the building environment. Gains or losses can be introduced in a BAS operation if humans are considered components of the system. To the best of our knowledge, no studies can be found that show evident gains or losses of integrating the human-in-the-loop in system design. To assess the impact of having humans performing clear and predefined roles in a BAS Cyber-Physical System (CPS) operation, we implemented a BAS case study.

Results: The initial results show that when the BAS consider humans more than CPS plant's elements, the BAS is more energy efficient while providing conditions that promote the user's health and productivity. With the experience gained with this work it will be possible to build in the future more resilient and effective participatory BAS.

Keywords: Cyber Physical Systems, Building Automation Systems, Human-in-the-loop, Internet of Things

RESUMO

Contexto:O planeta enfrenta desafios ambientais devido às emissões de dióxido de carbono. O consumo energético em edifícios representa entre 30% e 45% dos gastos mundiais de energia. É imperativo alterar estes valores para encontrar uma relação sustentável com o meio ambiente. Os Sistemas de Automação de Edifícios (SAE) têm como objetivo o aumento da eficiência energética de um edifício e maximização do conforto proporcionado aos humanos que utilizam o edifício. **Problema:** Os SAE frequentemente não consideram a participação humana como uma ferramenta que pode ser utilizada na obtenção dos seus objectivos. **Solução:** Os humanos podem assumir vários papéis nos ciclos de controlo de um SAE. Administradores de edifícios podem definir regras de controlo, utilizadores do edifício podem ser a fonte de dados que serão utilizados em tomadas de decisão automatizadas e o sistema pode requerer ações dos utilizadores que irão alterar as condições do edifício. Ganhos ou perdas podem ser obtidos se os humanos forem considerados componentes do sistema. Não encontrámos estudos que avaliem ganhos ou perdas que resultantes da integração do human-in-the-loop no desenho do sistema. Para avaliar o impacto dos humanos no desempenho de papéis pré-definidos no ciclo de controlo de um SAE, implementámos um caso de estudo de um SAE e realizámos experiências piloto.

Resultados: Os resultados iniciais mostram que SAEs que consideram os humanos mais do que elementos do sistema aos quais não são confiadas funções, demonstram ser mais eficientes do ponto de vista energético e ao mesmo tempo proporcionam condições que promovem a produtividade e o conforto dos ocupantes. Através da experiência adquirida com este trabalho vai ser possível a implementação no futuro de SAEs mais resilientes e receptivos à participação dos seus utilizadores.

Palavras-chave: Sistemas ciber físicos, Sistemas de Automação de Edificios, human-in-the-loop, Internet das Coisas

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ACRONYMS

AC	Air Conditioning.
AES	Advanced Encryption Standard.
API	Application Programming Interface.
BAS	Building Automation System.
BIS	Bispectral Index.
BLE	Bluetooth Low Energy.
CAD	Computer-aided design.
CBEMS	Cyber-physical building Energy Management System.
CEN	European Committee for Standardization.
CLADS	Closed-loop anaesthesia delivery system.
CPS	Cyber Physical System.
DHCP	Dynamic Host Configuration Protocol.
DNS	Domain Name System.
EER	Enhanced Entity-Relationship.
GPA	Global Plan of Action.
GPIO	General Purpose Input Output.
GPS	Global Positioning System.
HiTLCPS	Human-in-the-Loop Cyber Physical System.
HTTP	Hypertext Transfer Protocol.
HTTPS	Hyper Text Transfer Protocol Secure.
HVAC	Heating, ventilation and air conditioning.
ILO	International Labor Organization.

IoT	Internet of Things.
IP	Internet Protocol.
JAX-RS	Java API for RESTful Web Services.
JDBC	Java Database Connectivity.
JWT	JSON Web Token.
LAN	Local Area Network.
LED	Light-emitting diode.
MQTT	Message Queue Telemetry Transport.
ORM	Object-Relational Mapping.
PaaS	Platform as a Service.
REST	Representational state transfer.
SSL	Secure Sockets Layer.
TCP	Transmission Control Protocol.
TLS	Transport Layer Security.
UUID	Universally Unique Identifier.
VLAN	Virtual Lan.
WHO	World Health Organization.
XMPP	Extensible Messaging and Presence Protocol.

Chapter 1

Introduction

1.1 Context and Description

Cyber Physical System (CPS) are a specific type of systems that integrate computation and physical processes. In those, feedback loops, computational systems monitor and control physical processes, and physical processes affect computational processes [24]. Applications can be found in the automotive industry, healthcare devices, military systems, robotic systems, transport systems, building and environmental control and smart spaces. With the IoT revolution and the Industry 4.0 [13, 19] initiative that is under way, the costs to develop these systems are decreasing, making them more accessible to the industry and the common user. The expected impacts of the dissemination of CPSs on the economy are substantial [7], and the degree of their adoption and how they are integrated will be a factor in finding the competitiveness of an economy.

With the rise of environmental concerns and the increase in energy costs in the last decades, a new type of CPSs is emerging: BAS. Still lacking Engineering techniques to design and implement such systems, those are becoming one of the answers to address the mentioned issues. In 2004 data collected [50] showed that building energy consumption in the EU and the US was higher than the energy used for the industry or transportation.

The current work of this thesis is being developed in the context of the NOVALINCS research project named "SmartLab". This project, aims at building a CPS for BAS for the purpose to be simultaneously a case study and demonstrator of several systems concepts, such as:

- Building Automation - Automation of an open space laboratory.
- System-of-Systems - Study the integration of different CPSs that share the same environment.

- Deal with system conflicting properties - Maximise user comfort while reducing energy costs at design, implementation and runtime.
- System Modelling - choose the adequate abstraction levels, formalisms and tools to deal with this type of CPS. Choose the necessary systems views to deal with the different stakeholders.

This case study will help us to identify the difficulties of modelling humans at the level of abstraction that is necessary to the Smartlab to operate correctly while meeting its goals. With the artifacts created in the design stage, it will be an enabler to simulate the Smartlab operation using simulation tools. It will also be possible to identify the benefits and disadvantages of having humans performing the different roles in the feedback loop.

1.2 Motivation

Humans take traditionally the role of end-clients of CPS. Either by consuming the output of such devices (like monitoring, or getting the result of the actuation in the environment like in industry assembly lines) or soliciting operations from it. However, humans can also take a role as part of the system itself. Having humans performing cooperatively more roles in the feedback loop allows the CPS to operate in conditions where it is not possible to use electronic sensors or actuators or in situations of failure of this components.

Instances of CPSs where humans participate in the feedback loop are defined as HiTL-CPS. Humans may assume several roles in this loop [31] they may be involved in: the control, actuation stages, network communication or they are part of the environment in which the system operates. We can find HiTLCPS applications in several domains such as medical systems, where sugar level monitors are used to alert patients, driver attention systems in the automotive industry and crowd-sourcing systems found in smart cities.

The participation of Humans in the CPS can occur for several reasons. For instance, the participation may be necessary for situations where the complexity of the task can still not be completely solved with robotics. Also, when a system is taking decisions over actuation that has impact over individuals, having the input from the humans that are subject of analysis from this system may produce better operation results. In situations where a large number of sensors and actuators is needed for a CPS to perform its functions, allowing humans to perform these roles can make these systems economically viable to build and maintain. It also provides redundancy for failed feedback loop components like sensors, actuators or controller components.

As Munir, Stankovic, Liang and Ling state in their work [31], several challenges arise from human participation in the control phase. The role of humans in such systems is still very blurred and difficult to take into account in both design and run time. We argue that to incorporate human models in the design stage of an HiTLCPS as part of the system loop (and not just as the destiny of its final output) will enable to better optimise system parameters and to maximise multidimensional utilities, eg., maximising comfort while saving energy.

Although we believe that the results of our work will be applicable to CPS in general we concentrate our effort in BAS, which are a particular type of CPSs.

1.3 Problem Statement and Final Goals

Inverting the tendency of fully automating the systems deprecating the human participation, the goal of this work is to demonstrate that a human can turn the CPS more efficient towards the system goals while clearly performing all roles in the CPS feedback loop perfectly articulated with the hardware and computation as if he was another component of the system. Such as control, actuator, sensor and even part of the physical plant and system's environment. To the best of our knowledge, as we will discuss the next chapters, there is a lack of implementations that shows all those roles being used in an integrated fashion.

As the applications domains of CPS is very broad, in this thesis we are interested in researching HiTLCPS in the particular application Domain of BAS, where the conflicting properties of energy efficiency and comfort are deeply coupled with the CPS's main mission.

During our study, special care was taken to the fact that when humans performing the functions of sensors or actuators, the system has to take into account psychological and physical aspects of humans that can have an impact on reliability, confidence, robustness or even degradation of the system operation.

Our main goal is to answer to the following question:

- **Can we bring gains to the BAS CPS by designing the system to consider the Human in the Loop, with clear predefined roles, in a structured fashion as if a component of this system?**

To answer to this question we will have the opportunity to address the following sub-questions:

- What are the roles that a human can perform in a BAS CPS feedback loop?
- Does the system performance decays, because of factors like the lack of human engagement techniques?
- What challenges does this participatory environment impose to the systems resilience? Will it be the same as dealing with hardware/software components with certain precision and reliability?
- With HiTLCPS for BAS, can we still deal with the conflicting properties of energy consumption and comfort?

To answer this question, we analyse human participation in the case study described in Chapter 4. The case study should also demonstrate the benefits and the challenges of modelling humans at a CPS design stage.

1.4 Expected Key Contributions

Based on the research done during this thesis, the following contributions can be expected:

- Pinpoint the problems related to modelling a CPS, where humans perform several roles in the feedback loop.
- Build, Comission and Run a rich BAS case study. This case study will deal with energy consumption versus confort.
- Solve the complexity of integration different technologies typically not meant to be integrated because of vendor lockin. This problem involves heterogeneous IoT technologies with stream data analysis, cloud solutions, etc.

1.5 Document Structure

This document is organised in the following way:

- Chapter 1 - Introduction : this chapter is an overview this work.
- Chapter 2 - Background: an overview of CPS and human participation in these systems. Also, describes BAS in more detail.
- Chapter 3 - Related Work: in this chapter we present the participation of humans in different types of HiTLCPS, the study performed to choose the IoT platform to be implemented in the case study and we present the Portuguese legal framework related to the provided environmental conditions in workplaces.
- Chapter 4 - Smart Lab: a description of the Smartlab case study. We present the system at the physical level and the technologies used in the implementation.
- Chapter 5 - Empirical Studies: in this chapter we present three pilot empirical studies where we evaluate the effect on having humans performing different CPS feedback loop roles.
- Chapter 6 - Conclusions: in this chapter we present a summary of the work and future work.

Chapter 2

Background

2.1 Cyber Physical Systems

A cyber-physical system (CPS) is an integration of computation with physical processes whose behaviour is defined by both cyber and physical parts of the system [25]. For understanding the system, it is not sufficient to comprehend the physical part or the computational part separately. One also has to understand the intersection of this parts. Applications can be found in healthcare, energy systems, industry, building automation, transportation systems and in many other areas.

As the complexity of this systems increases, the development of CPS requires the involvement of multidisciplinary teams [38]. Individuals with a background in electronics, computer science and knowledge in the areas where the system will operate, are required to work together.

Three different parts can be identified in these systems:

- Physical Plant - corresponds to system components that are not realised by electronic components or digital networks. These parts can be humans, biological or chemical processes or mechanical parts.
- Computational Platforms - these components can be computers, sensors or actuators. A system has one or more than these platforms.
- Network Fabric - Interconnects computational platforms.

A CPS model commonly includes all three parts and additionally comprises the system static and dynamic properties. Many CPS are safety-critical and subjects of attacks [9]. System invariants and security concerns like availability, integrity and confidentiality should be addressed at system modelling phase.

A CPS operation can be abstracted as a loop composed of the following actions:

1. The physical plant provides data to the computational platform.
2. Sensors analyse and send the data to a control component.
3. The control part decides which command to send to the actuators.
4. The actuators actions can provoke changes in the physical plant state.

This loop is called a feedback control loop and its visual description is presented in Figure 2.1.

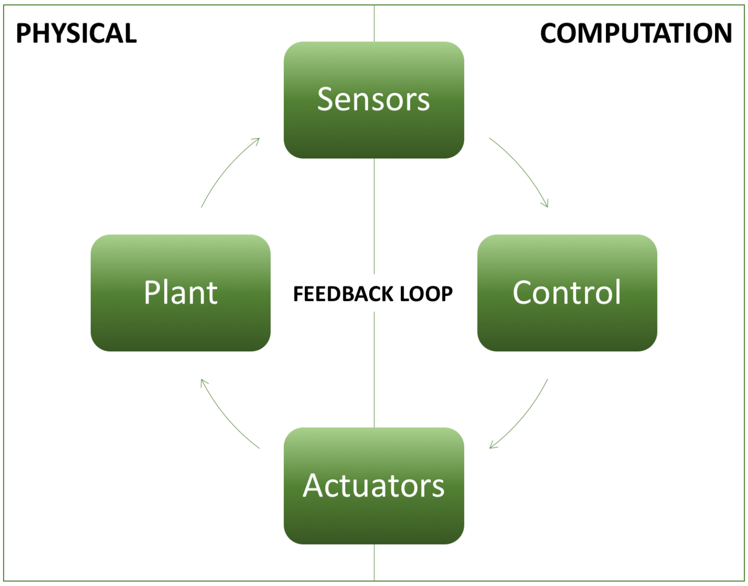

Figure 2.1: CPS feedback loop adapted from [25]

This loop is called feedback control loop and its visual description is presented in Figure 2.1. Two variations of the feedback loop exist: the open-loop and the closed-loop. In open-loop, the sensors capture the physical plant data and this data does not trigger any actions that change the physical plant state. The data collected can be stored. An example of an open-loop system is a CPS used human sleep tracking [21]. In a closed-loop system, physical plant data provided to the computational platform can trigger actuator actions that will change the physical plant state. An example of a closed-loop system is the smart thermostat [28] that detects occupancy and sleeps patterns for control Heating, ventilation and air conditioning (HVAC) systems. The goal of this system is to save building energy consumption costs.

2.1.1 Human-in-the-Loop Cyber Physical Systems

Human-in-the-loop cyber physical systems are instances of CPSs where humans participate in the feedback control loop.

Humans can be present in the following loop phases:

- Control - Applications can be found where humans directly control the system. Munir, Stankovic, Liang and Lin [31] identifies two ways where, a person exercises supervisory control. This control can happen in two ways:

    1. Humans define parameters in the control algorithm, and the system operates within the established boundaries.
    2. The system receives a command from humans, and then the command is executed. In the end, the system waits for further commands.

- Physical Plant - Humans can be part of the system physical components. They can be the source of the sensors analysed data, the target of the system actuation mechanisms or merely because their presence can alter the physical plant state.

- Actuators - In some situations, artificial intelligence or robotic equipment still are not capable of performing actions that humans can fulfil. In this cases, human action is required to achieve the desired physical plant state.

- Sensors - It is our belief that humans can also perform the sensor role. This possibility does not comply with the definition presented in section 2.1 because sensors are included in the computational platform. We believe that in systems that actuate on the environment where humans are part of, having humans performing the sensor role will be valuable in following scenarios:

    - Failure of sensor components. In situations where people can provide an approximate assessment of the physical plant conditions. A possible scenario could be the replacement of a failed temperature sensor by feedback provided by a person.
    - Different individuals can assign different satisfaction indices for the same environment parameter value. The assessment provided by each individual will contribute to the controller's decision.

These systems rely on human as data sources, control or actuation; therefore it is important to consider humans part of the system and they should be a central concern in the system modelling phase.

Modelling human behaviour or physiological aspects is a very complex task due to their heterogeneity [1, 42]. It is then important to model humans at the right level of abstraction to ensure the HiTHLCPS operation.

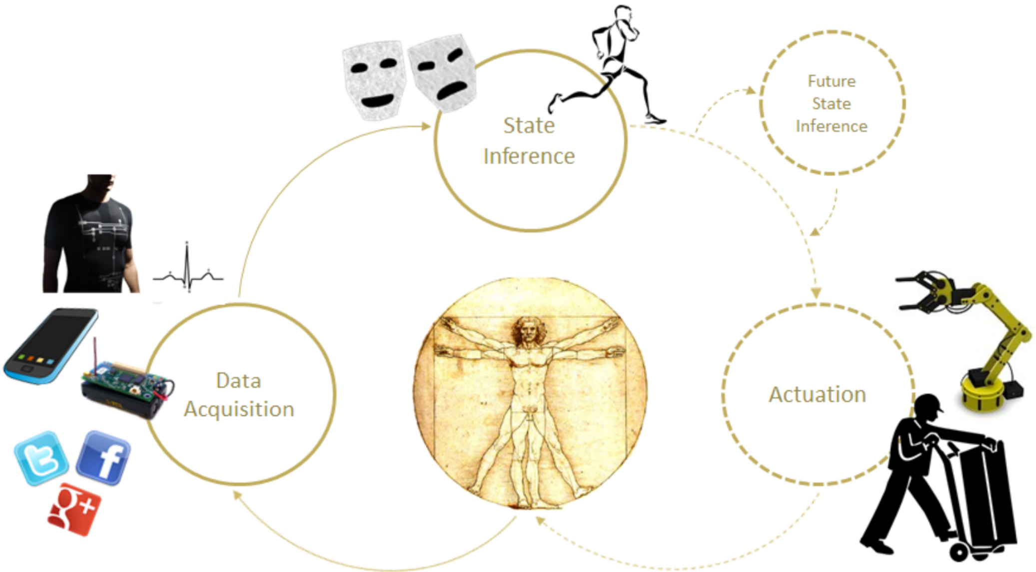

Figure 2.2: Human-in-the-loop Control. Taken from [42]

2.1.2 Building Automation Systems

Buildings energy consumption is responsible for thirty to forty-five percent of global energy consumption. It is imperative to reduce these figures because of the environmental challenges that we need to address, and the fact that the energy costs are determinant to assess the competitiveness of a country's economy. Regulamentation is also beeing issued by the European Commission with the objective of having nearly zero-energy building by 2020 [3].

To achieve these goals a new class of CPS has emerged: the Cyber-physical building Energy Management System (CBEMS) [46]. These systems deal with apparently conflicting goals like making buildings more energy efficient while maximising occupants comfort and optimising building functions. These automation systems can be deployed in new or existing buildings [6]. BASs are formed by a set of networked components that monitor and actuate on the building environment and control a variety of functions like:

- Energy generation and storage systems.
- HVAC.
- Lighting and shading.
- Occupation detection.
- Security systems.

2.1.3 Architectures

A commonly adopted [14, 26] architecture for BAS is divided into three levels:

- Management - It is at this level that data is analysed and stored. Analytics, reports and performance data is presented to building operators and users. Control rules are defined at this level that will propagate to the lower levels.
- Automation - The control infrastructure is implemented at this level. Control rules defined at the management level by building operators are the basis of the executed control loops. The higher level can delegate data pre-processing functions to this level.
- Field - Devices that interface with the physical plant are located at this level. These devices can be sensors, actuators or network components. Building equipment settings are applied at this level.

The three-level architecture is presented in Figure 2.3.

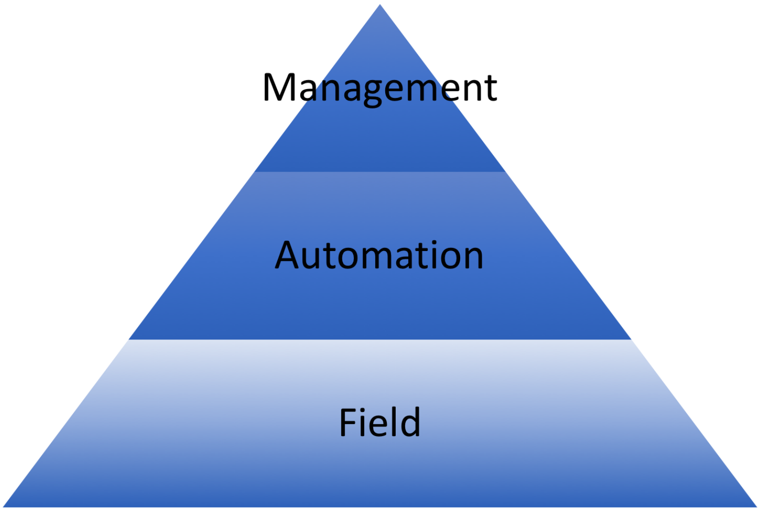

Figure 2.3: BAS Architecture

2.1.4 Agents

[46] propose a variation to the 3 level architecture. A fourth layer responsible for data acquisition and interface is hierarchically placed between the field and automation levels. This layer provides communication services modules and sensor middleware that communicate with agents through the TCP/IP protocol stack. Agents are responsible for pre-processing data received from the physical plant sensors and transmitting the processed data to the automation layer. In the context of a BAS, an agent could be responsible

for processing sensor data from a building area, e.g., room, floor. An agent can also be a specialised instances with a particular hardware configuration optimised for processing a specific sensor type data.

In Figure 2.4, we present an abstraction for an environment agent.

The case study presented in Chapter 4 implements a similar architecture where the main difference is that agents do not connect to sensors using the TCP/IP protocol stack exclusively.

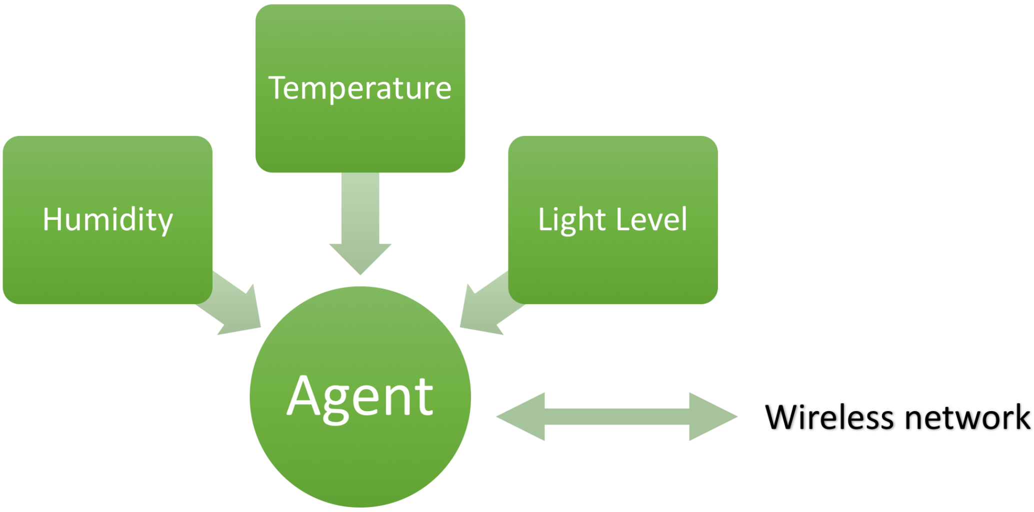

Figure 2.4: Environment Agent adapted from [46]

Chapter 3

Related Work

3.1 Human-in-the-loop Cyber-Physical Systems

As mentioned in Chapter 2, section 2.1.1 humans can assume the feedback loop roles of sensor, control, actuator or part of the physical plant. The understanding of the roles, tasks, and expected behaviour will bring us relevant priory knowledge for the purpose of prediction, simulation, and contingency planning. This will allow us to build a more resilient systems while accomplishing its mission.

To study human participation in CPSs we analysed several systems in different areas where humans perform different roles in the feedback loop.

In this section, we present examples of HiTLCPS in the areas of healthcare and BAS.

Through the analysis of other areas than BAS, we will assess human impact in the performance of the system and techniques used for integrating humans in the feedback control loop that are applied in BAS.

In Table 3.1 we present an overview of the roles that humans perform in the three areas. We found examples in all areas where human assume all the available feedback loop roles except the sensor role. In the automotive industry, humans can assume the role of supervisory control when adjusting an automatic suspension system. They assume the role of actuators in a tyre pressure monitoring system when system raises the alarm when tyre pressure is below the minimum set-point and it is the human is responsible for inflating air into the tyre. Finally, the human is part of the physical plant in a driver attention detection system [12]. The system collects visual information about the driver and tries to infer the driver attention state.

	Physical Plant	Sensor	Control	Actuator
Healthcare	●	○	●	●
BAS	●	○	●	●
Automotive Industry	●	○	●	●

Table 3.1: Analysis of human participation in HiTLCPS of different areas. Legend: information not found, does not participate as role ○, participates as role ●.

3.1.1 Healthcare

In health-care industry, several CPS are being used to provide better, safer and cost-effective medicine to the patients [34]. One of the mainstream examples derived from the anaesthetic practice in which the reinforcement learning is also taking the first steps [30].

Anaesthesia is a reversible state of coma, in which the patient is unresponsive to the external stimulus. During this process, several output measures (physiological parameters from the patient) are being recorded, every second. Then, they are analysed by the anesthesiologist (actuator) who decides if there is a need of changing, for instance, the drug infusion rate. Considering propofol (a commonly used drug to induce and maintain anaesthesia) as an example, an increase in propofol rate will produce a consequent decrease in a measurable physiological parameter – the brain activity, which can be recorded by a Bispectral Index (BIS) monitor [32]. The BIS software transforms the brain activity into a number within the following range, 0 to 100. A BIS of 0 reveal no brain activity, in the opposite, a value of 100 occur in an awake patient. In an anaesthetized patient, the BIS value should not be lower than 40 nor higher than 60. Taking this into consideration, several efforts are being made to produce and validate the anaesthetic closed-loop system. A closed-loop system, within the anaesthesia community, is a feedback-guided system [37]. Presently, two feedback loop guided systems are available: the Closed-loop anaesthesia delivery system (CLADS) and CONCERT-CL [27]. This definition contradicts the one presented in Chapter 2, Section 2.1, which shows the lack of consensus, in this matter, between different scientific communities.

At the beginning of the anaesthesia, the anaesthesiologist sets the alarm range values (between 40-60) in BIS console. If a BIS value below 40 is recorded (over-anaesthetised patient), an alarm is raised, and the anesthesiologist decreases manually the infusion pump drug delivery rate. The corresponding CPS feedback loop is presented in Figure 3.1.

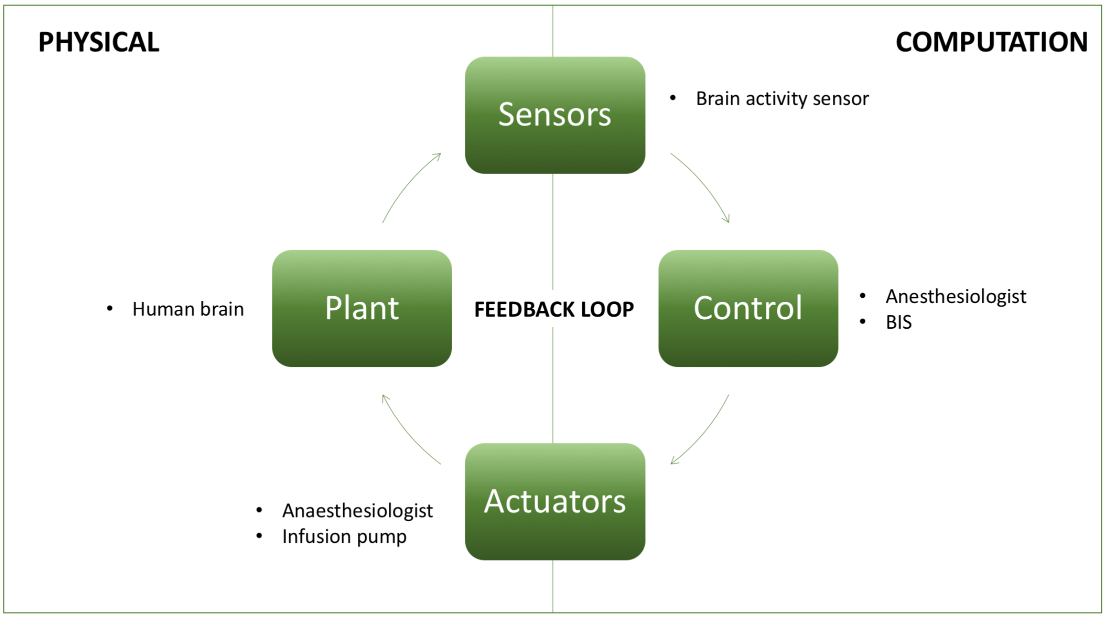

Figure 3.1: An anaesthetic procedure with anesthesiologist as an actuator.

In a feedback loop system where the anesthesiologist does not participate as an actuator but only as a controller, the controller component automatically detects a decreased BIS value and actuates in the infusion pump delivery rate, reducing it. Feedback loop guided systems have a single actuator: the infusion pump as described in Figure 3.2. If the system detects a value higher than the alarm range upper limit, the reverse procedure will take place.

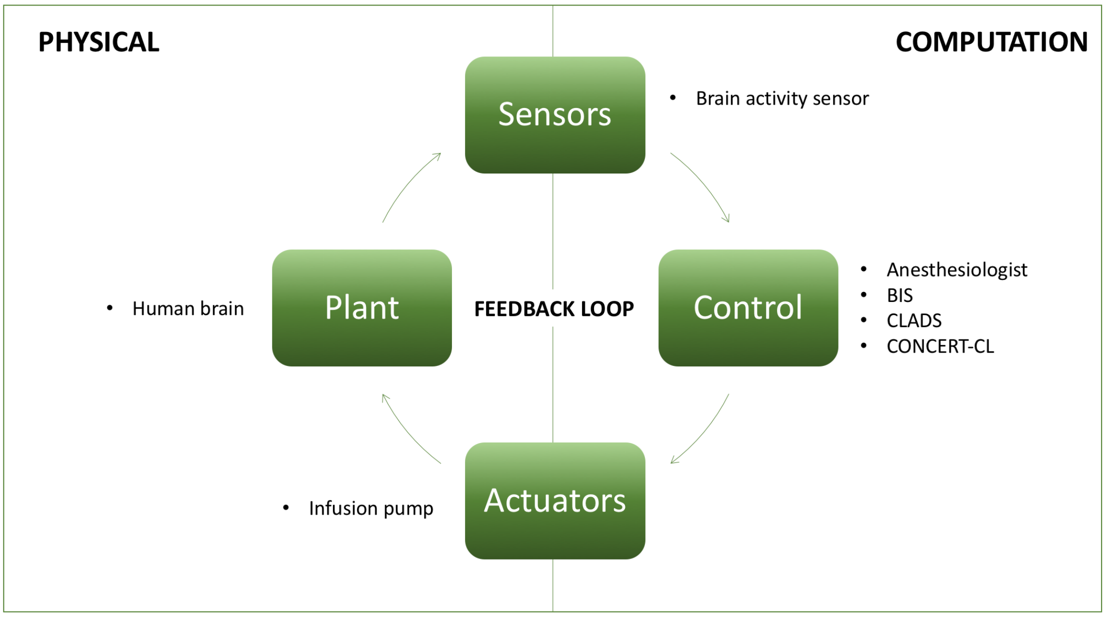

Figure 3.2: An anaesthetic procedure without anesthesiologist as an actuator.

Several advantages concerning this kind of systems are being pointed out: freeing the anaesthesiologist of repetitive tasks which allows him to maintain high level of vigilance during all the procedure [39], reducing the workload of anaesthesiologists and accurate control of targeted BIS and hemodynamic parameter levels.

In two trials [27, 37], the feedback loop guided systems achieved better results than the system where human performed the actuator role.

3.1.2 Building Automation Systems

When studying examples of BAS where humans participate, we set the focus on case studies that have as an objective to maximise comfort parameters.

Zeiler, Vissers, Maaijen and Boxem [53], presented a BAS case study where the objective is to explore the impact of the building occupant's behaviours on energy consumption. Current HVAC installations that don't take into account the building occupants behaviour, often do not reach the intended comfort levels. This situation occurs because the individual comfort level is not monitored and the system goal is to provide a room with a certain temperature. A higher value of energy savings is obtained when the system focus on providing better conditions to an individual, as occupants tend to overturn actions when they feel uncomfortable. This behaviour leads to a higher energy consumption. The developed system monitors the perceived user temperature and actuates upon that data. The system preemptively enters into action when it detects situations where the human is about to initiate an action which could lead to energy waste. It acts by changing the temperatures conditions while minimising energy consumption. The authors reached the conclusion that human influence is three to five times higher than variations in building parameters and that the human-in-the-loop approach leads to energy savings.

In this case study, the human performs the physical plant role in the BAS feedback control loop. It is our belief that a system where the human performs the sensor role in the feedback loop could result in similar energy savings and improve the user satisfaction as the user would not have to carry the body sensor during his work. The cost to develop, deploy and maintain would be inferior to the presented solution.

3.2 Internet of Things Platforms

An analysis of the available IoT platforms was necessary to select which platform should be implemented in the Smartlab project.

Significant differences regarding processing power, memory, storage, connectivity and battery capacity exist between IoT devices. It is then necessary that the chosen platform has to provide support for a variety of IoT devices or support for integration of new IoT devices that are launched on the market every day. In the context of this work, this is an important feature, as the case study presented in Chapter 4 consists in implementing a

BAS in an environment where automation does not exist and automation solutions have to be developed for the existing equipment.

IoT applications, devices, and platforms have available application layer protocols suited for the existing IoT devices heterogeneity [2, 20]. IoT platform support for application layer protocols popular in the IoT community like Message Queue Telemetry Transport (MQTT), MQTT, Representational state transfer (REST) Services and Hypertext Transfer Protocol (HTTP) is important as it will provide more flexibility for application development and increase support for devices and different buildings networks configurations.

IoT Platforms with different system architectures are available. Public or Private PaaS [51] like Amazon AWS IOT, Microsoft Azure, IBM Bluemix or WSO2 IOT server are available.

Functional and non-functional requirements for the IoT platform were identified. The main functional requirements are:

- Custom devices support.
- Comprehensive support for IoT application protocols, e.g., MQTT, Extensible Messaging and Presence Protocol (XMPP), RESTFUL Services, HTTP.
- APIs available for device, user and data management.
- Authentication and access control of devices and users.
- External system integration.
- Data Analytics.
- Protected communications between IoT devices, users and IoT platform.

A list of non-functional requirements was defined:

- Open Source.
- Data Integrity and Confidentiality.
- Reliability.
- Availability.
- Performance.
- Maintainability.
- Interoperability.
- Confidentiality.

An initial analysis of the requirements was made and three platforms were added to the shortlist. Two public Platform as a Service (PaaS): IBM Bluemix and Microsoft Azure. The third option is the private PaaS: WSO2 IOT Server.

	WSO2	Azure	IBM
Custom Devices	●	●	●
Device management	●	●	●
Device management API	●	●	●
Integration	●	●	◐
Device and User Authentication and Access Control	●	●	●
Protected Communications	●	●	●
Analytics	●	●	●
Portal	●	●	◐
Management API availability	●	●	◐
Data Control	●	○	○
Open Source Code	●	○	○
Free to use	●	○	○

Table 3.2: Comparison of key concepts of the analysed IoT platforms. Legend: information not found, no support ○, partial support ◐, full support ●.

	WSO2	Azure	IBM
MQTT	●	●	●
HTTP	●	●	●
XMPP	●	◐	○
RESTFUL Services	●	●	●
Custom protocols	◐	◐	○

Table 3.3: Comparison of IOT application layer protocols support . Legend: information not found, no support ○, partial support ◐, full support ●.

A comparison of the initially selected platforms was made, and after considering the system requirements, the WSO2 IOT Server platform was chosen. A key element of the decision was that WSO2 provides full data control. Unauthorised access to the data could potentially lead to the disclosure of personal data or habits of the laboratory occupants. Another factor that contributed to the decision was the platform open source license. This license provides the rights to study, change and distribute the software. The open source license was recognised as an advantage over the other considered platforms. It is our belief that having the power to customise the solution will increase the support for end-of-line equipment or new IoT devices, and expand the possibility of integrating with different systems.

3.3 Workplace Environmental Conditions

3.3.1 Legal Framework

The environmental workplace conditions are an essential factor for maintaining the worker's productivity at a high level. If the workplace temperature is very high, workers may suffer from lack of concentration, headaches and the stress levels may increase. The workplace conditions regulations vary from country to country. Some countries adopt the Word Health Organization recommendations for temperature, humidity and light conditions. The WHO states that a comfortable temperature in the workplace is in the range 16 to 24 degrees Celsius. In Portugal, the workplace conditions are defined by the Decree Law 243/86[1] from the 20th of August. The regulation sets not only the necessary environmental conditions, but it also defines the safety procedures, the minimum physical dimensions for a workplace, the support facilities, the entities responsible for inspection and, the sanctions for companies that not comply with the norms. Recently additional legislation focusing on buildings thermal behaviour was approved. The Decree Law 80/2006 defined the Regulamento das Características de Comportamento Térmico dos Edifícios (RCCTE) that defines a building thermal behaviour. In the context of this work, we will focus on the temperature and light conditions.

The Decree-Law 243/86 indicates that the facilities must provide an environment that promotes the workers' health and their well-being. This legislation sets as a goal for the temperature at the workplace, a temperature in the range of 18 to 22 degrees Celsius and, in exceptional meteorological conditions the temperature can reach the 25 degrees Celsius. It is important to stress that these are merely guidelines and they should be applied if it is possible. The legislation also states that workers should not face sudden changes in temperature. The humidity level should be inside the range from 50% to 60%.

Table 3.4: ILO proposed illuminance levels for different tasks or locations

Task\Location	**Maintained illuminance (lux)**
General offices	500
Computer workstations	500
Rough work	300
Medium work	500
Fine work	750
Instrument assembly	1000
Jewellery assembly/repairs	1500
Hospital operating theatres	50000

The luminosity levels must comply with the requisites defined by the International

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[1] https://dre.pt/web/guest/pesquisa/-/search/219080/details/normal?q=243%2F86+20+de+Agosto (accessed 25-03-2019)

Labor Organization's (ILO) Model Code of Safety regulations[2] for industrial establishments for the guidance of Governments and Industry, while the Portuguese legislators do not rule on this subject. In table 3.4 are presented the maintained illuminance values recommended for different types of tasks.

In 2019, the Portuguese government issued resolution 28/2019[3] where it acknowledges that appropriate environmental, psychological and organisational conditions are essential factors to achieve high levels of worker's productivity. The government also recognises that work-related accidents and diseases have an impact on the Gross domestic product and that higher levels of security and health at the workplace will improve the worker's life quality and improved theirs working capabilities. To reach these goals, one of the proposed measures is to develop plans that focus on health and security at the workplace. The plan will focus on:

- Evaluation of the workplace environmental conditions. Light, temperature, ergonomic, air quality, and noise conditions will be evaluated.
- Human life safety - Emergency drills and first aid training.
- Preventive health care and the adoption of a healthier lifestyle.
- Raise the workers' engagement in activities that promote team spirit building and improve the recognition of their work.

3.3.2 Health at the workplace

Promoting health in workplaces is vital for business productivity and to counteracting workers' disability. Nearly two million people are estimated to die as a direct consequence of occupational illness[47]. Several initiatives, endorsed by the World Health Organization (WHO), are taken place worldwide to tackle this issue. Summarised in five objectives, the Global Plan of Action (GPA) guides occupational health promotion and implementation strategies since 2007[48]. Concerning offices, occupational hazards include awkward postures, repetitive motions, insufficient pauses and inadequacy of workstation setup in terms of environmental conditions such as light and temperature, among others[44]. In fact, bright light exposure is protective against and delays myopia[33][23], a ubiquitous' eye disease expected to affect, by 2050, as much as 52% of the world's population[45]. The computer vision syndrome, an amalgamate of eye's signs and symptoms related to computer exposure, evolves very often this kind of refractive eye's defect with inappropriate work conditions[4]. Changeable light hazards in offices prone to be monitored include illuminance levels and luminaire brightness[18]. The adequate luminance levels according to the European Committee for Standardization (CEN) range from 500 to 750

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[2] https://www.ilo.org/safework/info/standards-and-instruments/codes/WCMS_218458/lang–en/index.htm (accessed 25-03-2019)

[3] https://dre.pt/web/guest/pesquisa/-/search/119487065/details/normal?q=Resolução+do+Conselho+de+Ministros+n.%202 (accessed 25-03-2019)

lux[11], to perform tasks like data processing and technical drawing. In this sense, efforts should be made to fit light conditions to the worker characteristics (age, eye diseases, etc.) and the task performed, to increase productivity. Another environmental factor closely linked to productivity is room temperature[49]. There is robust evidence that the highest performance is achieved at 22ºC[41]. Beyond 21-24ºC range, the impact of symptoms caused by the Sick Building Syndrome are more intense and contribute to decreasing labour efficiency. According to CEN, the recommended operative temperature to landscaped office with HVAC systems varies from 20ºC to 26ºC, during the winter and summer season, respectively[10]. Hence, the challenge is to reduce the energy cost of both environmental light and temperature conditions and link it to the best workers' productivity.

Chapter 4

System overview

4.1 Description

Our case study [40] is part of NovaLincs's Smartlab project [8]. This project is running in a laboratory located in the Faculty of Sciences and Technology (FCT NOVA), Computer Science Department. The space is used by MSc and PhD students as a computer science openspace. During their study cycles, students perform different tasks that present various energy consumption profiles . Generally, tasks like the compilation of software code or the deployment of systems are more energy demanding than the writing process of a thesis.

Inside the room, there is fish tank installed, managed by the Open Aquarium[1] hardware solution.

The Smartlab project has its main goals:

- Automation of energy-related and user comfort tasks.
- Maximisation of user comfort while reducing energy costs.
- Integration of CPSs and preservation of system invariants.

Two CPSs can be identified: the laboratory room and the fish tank. The Fish tank CPS can be considered as a subsystem of Smartlab CPS.

The laboratory CPS is an instance of an Intelligent Building Automation System [29], and the system aims to provide the best environment conditions for the users to develop their work.

The laboratory has temperature, light and power sensors available that allow monitoring of comfort parameters and energy consumption of the power sockets available to

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[1] https://www.cooking-hacks.com (accessed 25-03-2019)

the students and the fish tank subsystem . There are also available actuators that make possible to the system to control the energy consumption and comfort parameters.

In Section 2.1 a visual representation of a general purpose CPS feedback loop is presented in Figure 2.1. We present in Figure4.1 a Smartlab instantiation of the general CPS feedback loop definition. Each part of Smartlab CPS will be described in more detail in the next sections.

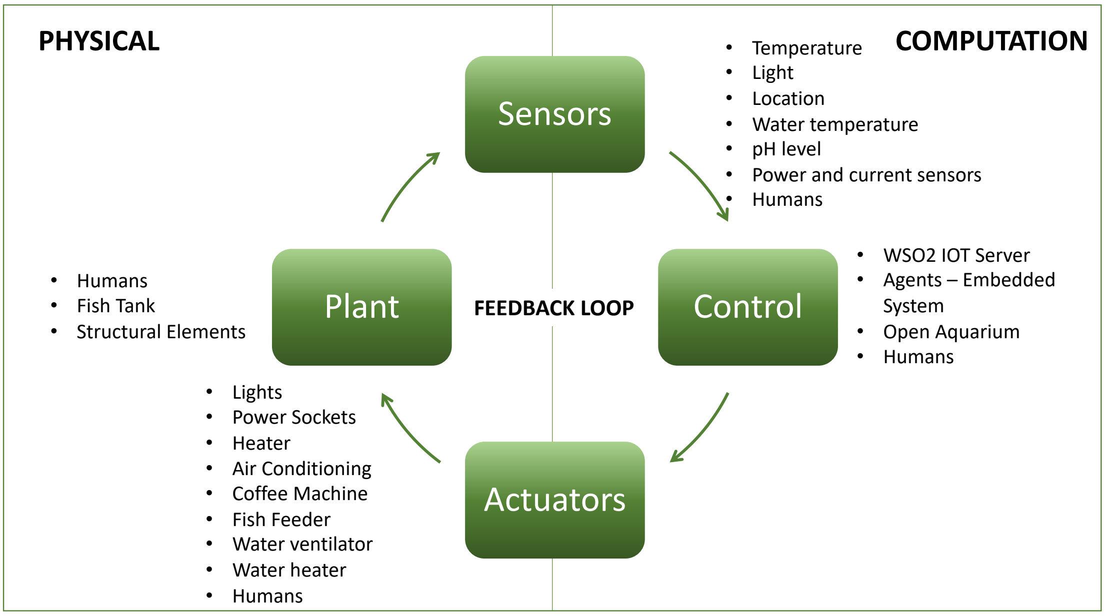

Figure 4.1: Smartlab Feedback Control Loop

The goals of this case study are:

- System Modelling - choose the adequate abstraction levels, formalisms and tools to deal with this type of CPS. Choose the necessary systems views to deal with the different stakeholders.
- Identification the difficulties of modelling humans at the correct level of abstraction during the design stage of the CPS.
- Study of the benefits and disadvantages of having humans performing the sensors, actuators and control roles.

4.2 Plant

As mentioned in the previous section the Smartlab environment is a computer science laboratory. There are eight workstations and a meeting table available for MSc and PhD students. The physical plant is composed by:

- Humans. Their presence can produce heat that changes the laboratory temperature or trigger actions that will alter energy consumption.

- Structural elements like doors, windows, beams and furniture.
- Fish tank subsystem. Changes in the laboratory environment can provoke alterations in the fish tank physical plant and vice-versa.

A physical model of the laboratory was built in DWG and DXF file formats using AutoCAD 3D (© Copyright 2017 Autodesk, Inc [2]). Software libraries like Teigha, RealDWG and LibreDWG are available for the creation of applications that can analyse and alter the model.

We defined structural elements like walls, beams and windows frames. Furniture and the equipment that is used for automation is also included in the model. All items are represented in separate layers. This procedure makes possible an easy visual identification of all the elements using visualisation tools, and the identification of model elements using software that supports the DWG or DXF file formats.

This model could serve as a valuable tool for simulating and decision support, of Building Automation behaviour and a basis for a visualisation tool for the results.

A 3D model of the laboratory is presented in Figure 4.2.

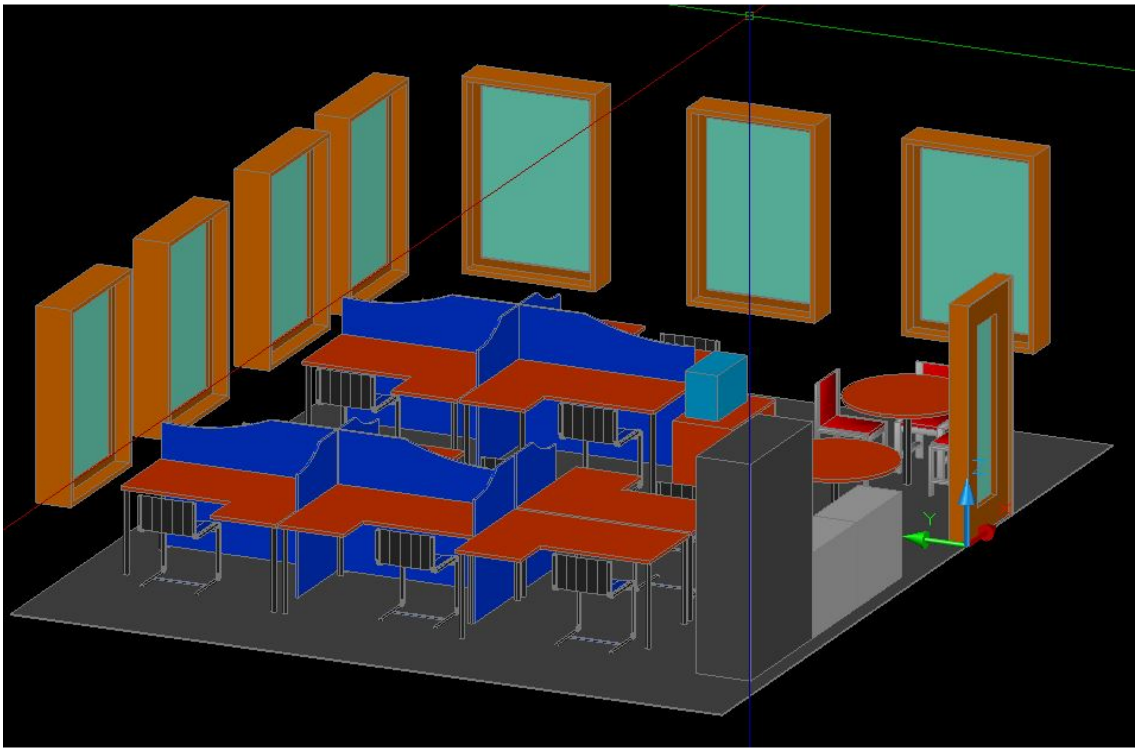

Figure 4.2: Smartlab 3D model developed in CAD, containing the structural information of the laboratory

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[2] https://www.autodesk.com (accessed 25-03-2019)

4.3 Sensors

As mentioned in the previous section, several types of sensors are available for capturing the physical plant state.

The next table presents the features of the sensors available in the laboratory.

Table 4.1: Room Sensors Available

Component	Description
Estimote Beacons	Temperature and Light sensors, indoor location system.
Power Sockets	It is possible to measure power consumption in Watts, current in Amperes.
Efergy Power Clamps	Measures in Watts the electric circuits power consumption.
DS18B20 Digital temperature sensor	Measures in degrees Celsius the outdoors temperature .
TSL2561 Digital Light Sensor	Measures in Lux the outdoors light level.

The next table presents the sensors available in the Fish tank CPS

Table 4.2: Fish Tank available Sensors

Component	Description
Water level sensor	Measures the aquarium's water level.
Ph sensor	Measures the water pH.
Conductivity sensor	Measures the aquarium's water conductivity levels.
Temperature	Measures the water temperature.

The Fish Tank CPS sensors and actuators are described in Table 4.2.

Considering the three level architecture presented in Chapter 2, section 2.1.3, sensors are part of field level.

4.3.1 Sensor Calibration

Several sensors that are used by the Smartlab project required an initial calibration process.

The Estimote beacons presented in Figure 23 require calibration for the temperature and light sensors. The temperature sensor is enclosed in a silicone casing and for this reason is not able to record sudden changes in the surrounding environment temperature. A reach-in climatic chamber for temperature and climatic testing Aralab Fitoclima 300ECP45[3] was used to calibrate and test the temperature sensor's accuracy, offset, precision and response time. Aralab's technicians provided support during the procedure.

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[3] http://www.aralab.pt/wp-content/uploads/2016/09/Aralab-TESTING-FitoTerm-and-FitoClima-reach-in-Climatic-and-Temperature-testing-chambers-DC045EN.pdf (accessed 25-03-2019)

After the calibration process, all thirty-three beacons temperature sensors work as described in the manufacturer specifications. In situations were the environment temperature changes significantly and quickly the sensor's response time reaches fifteen minutes. This is an essential factor that we took into account in the control algorithm implementation as it can take several minutes to the temperature sensors to detect changes in the environment.

It was also necessary to calibrate the TSL2561 and the Estimote luminosity sensors. We used the Velleman DEM301[4] light meter as a reference for the calibration values.

The Open Aquarium's pH and conductivity sensors were calibrated with the support of the FCT Nova Chemistry Department Professors Cristina Costa and Jorge Lampreia.

The pH sensor starts with the collection of sensor readings for pH four, seven and ten solutions. These saved values are used as arguments in the provided Open Aquarium library sensor calibration function. The conductivity sensor calibration process consists in collecting the sensor reads for 10500mS and 40000mS solutions. Again these saved values are used as arguments in the provided conductivity sensor calibration function.

4.3.2 Indoor Location System

To achieve the Smartlab project goals the system needs to be aware of the laboratory users presence. The users' movement inside the laboratory is an essential input for a control algorithm that aims to provide optimal environmental conditions to workers and predicts user actions that can lead to energy waste. As we are working in an indoor environment, it is not possible to rely on popular systems like Global Positioning System (GPS) and Global System for Mobile communication (GSM) antennas triangulation.

Our choice relied on Estimote Bluetooth Low Energy (BLE) beacons [17], as this system requires only that the users being tracked carry with them an Android or iOS smartphone, that supports a Bluetooth version higher than version 4.2. Each beacon runs on a low-power ARM 64 MHz CPU, with 512kB flash memory, 64kB RAM and is battery powered. Two positioning methods are available: Estimote Monitoring and Indoor Location. Android and iOS Software Development Kits are available for both modes. Two positioning methods are available: Estimote Monitoring and Indoor Location. Android and iOS Software Development Kits are available for both modes. The Estimote Monitoring gives the opportunity to developers to set different zones associated to one or several beacons. Each zone is defined by a tag that is periodically broadcasted and a radius around the beacon. An example is presented in figure 4.3. Entering and exiting the beacon area, triggers application events.

The Indoor Location requires the placement of at least four beacons around the monitored space. It is also necessary that the developer creates a map of the room. An application that interactively supports the map creation is made available by Estimote. Developers can alternatively create the map programmatically. The Indoor Location

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[4] https://www.velleman.eu/products/view/?id=421064 (accessed 25-03-2019)

mode returns at the application level the user coordinates relative to a room's point. An example is presented in figure 4.4. Both methods are implemented and working, but the control component relies exclusively upon the Estimote Monitoring mode. We believe that in a next iteration of the control component, the Indoor Location mode will be an essential component to implement a system that predicts user actions based on the user the movement trajectories inside the laboratory.

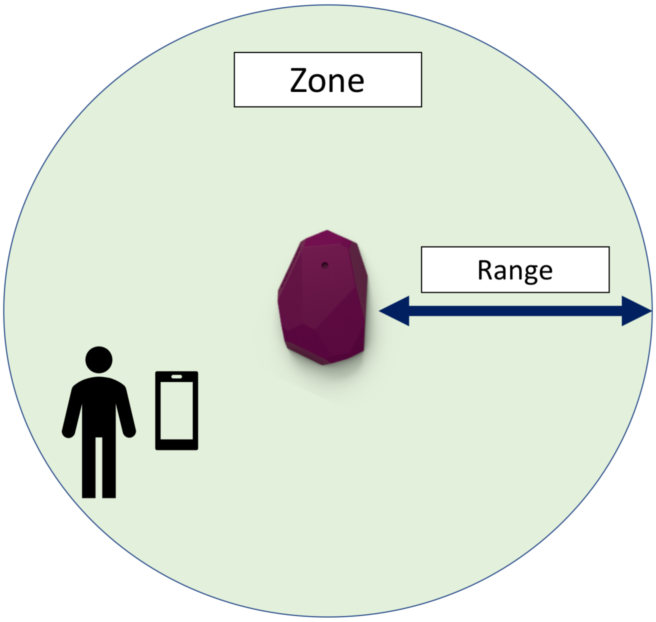

Figure 4.3: Events triggered by the user proximity to the beacon

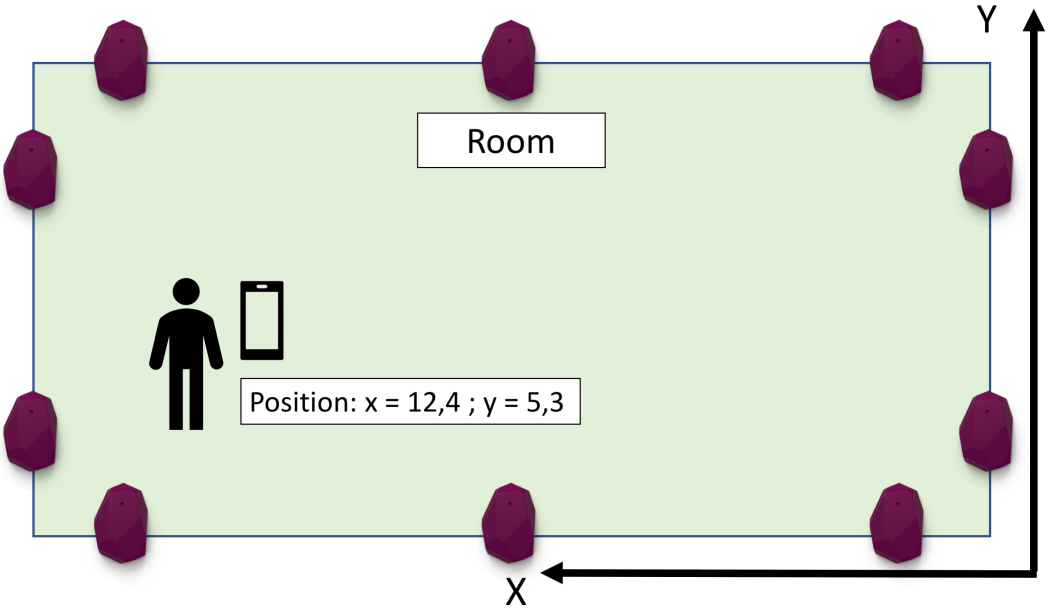

Figure 4.4: User position coordinates are available at the application level

4.4 Actuators

The Smartlab CPS has a set of actuators available that will allow actions triggered by the control component to provoke changes in the physical plant.

In Figure 4.3 we present the actuators available in the laboratory CPS and in Figure 4.4 we present the actuators available in the fish tank CPS.

Table 4.3: Laboratory available Actuators

Component	Description
Power Sockets	Power sockets can be enabled or disabled.
Lifx Lights	Power can be set on or off, hue, saturation and brightness values can be changed.
Coffee Machine	Used by the laboratory users and visitors.
Heaters	Used for increasing the room temperature.
Air conditioner unit	Air conditioner unit that used to set a desired room temperature. Power can be set on or off and several functioning modes can be selected.
Halogen lights	Halogen lights power can be set on or off.

Table 4.4: Fish Tank available Actuators

Component	Description
Ventilator	When activated, the ventilator lowers the water temperature.
Lights	Freshwater aquarium plants were placed inside the aquarium. These plants need light exposure during a period of the day.
Feeder	Releases food into the aquarium at the scheduled time.
Water Heater	Increases the water temperature.

Considering the three level architecture presented in Chapter 2, section 2.1.3, actuators are part of field level.

4.5 Control

During this work, an IoT solution was implemented. This solution already supports data acquisition and filtering from the available sensors, dashboards for data visualisation, user and device management. Supervisory control is available to the users, but to reach the goal of an autonomous system that makes decisions about energy consumption and comfort parameters, control rules have to be defined and deployed in the Smartlab controller.

The main Smartlab components are:

- Agents are responsible for filtering data received from sensors and after a decision that the data is relevant, the information is sent to the server component.

- IoT Platform - WSO2 IOT Server and MySQL Server. This component is responsible for data analysis, data presentation, authentication of users and agents, API and device management.
- Mobile Android application.
- Voice Interaction - Provides support for voice interaction between the laboratory users and the system.
- The fish tank CPS Open Aquarium controller.

The case study system architecture is similar to the 4 layer BAS architecture presented in Section 2.1.4. The main difference is that agents do not connect to sensors using the TCP/IP protocol stack exclusively.

An overview of architecture is presented in figure 4.5. In the next subsections each component is presented in more detail.

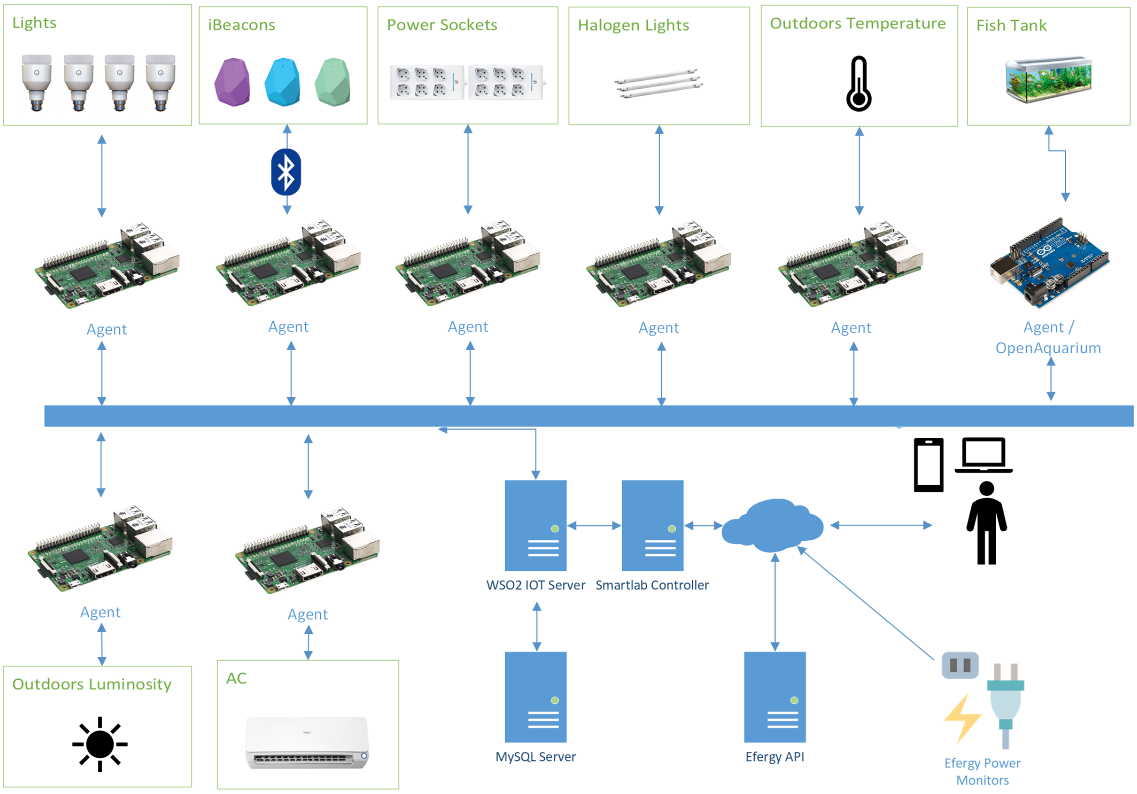

Figure 4.5: Overview of the solution architecture

This solution is already available in a production environment and the data collected from the Smartlab sensors is stored and accessible in the server component. It is also possible to set the state of the Smartlab comfort conditions like temperature and light level.

4.5.1 Open Aquarium

One of the goals of the Smart lab project was to build an autonomous fish tank CPS where human intervention is only necessary to refill the fish feeder, change water, and refill the water reservoir.

The main functional requirements of the fish tank solution are:

- Customization of the solution has to be possible to ensure the integration with the WSO2 IoT Server.
- Support of variations of the sensors and actuators set at any project stage.

Considering all project requirements, the Open Aquarium solution was chosen. Open Aquarium was created and is distributed by Cooking Hacks. The software is available as open source and customization is possible. The aquarium solution is presented in Figure 4.6.

Figure 4.6: Open Aquarium solution

The controller component is installed in a Arduino Uno [5] and all the necessary sensors are connect to the Open Aquarium shield. The platform hardware is presented in Figure 4.7.

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[5] www.arduino.org (accessed 25-03-2019

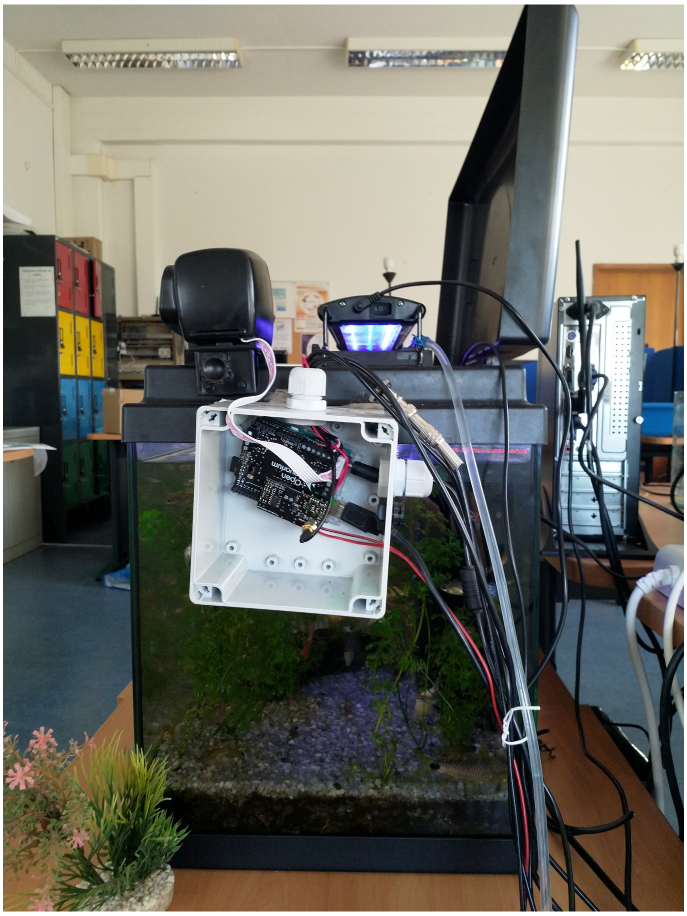

Figure 4.7: Open Aquarium processing components

All the hardware components were assembled during this thesis. During the test phase, the automated fish presented an erratic operation. The feed operation consists of one full rotation of the fish container, and occasionally the feeder would not stop rotating, releasing all the food on the aquarium's water. After the resolution of a support ticket by Cooking Hacks, the Arduino board was replaced. The fish feeder continued to present the same issues, and after analysing the Open Aquarium library code functions that control the fish feeder, we identified and fixed the problem. The provided function assumed a fixed rotation period and when small changes occurred the controller missed the time window where the feeder position indicated a full rotation had happened. We set a higher time period where the sensor position is analysed for a full rotation.

We also detected and solved a problem with the water level sensor. The provided Open Aquarium function that processes the sensor mistakenly reports a low water level when the water level is at an appropriate level. After changing the library code, the sensor started working as expected.

Considering the three level architecture presented in Chapter 2 section 2.1.3, the Open Aquarium solution has components that are part of the automation level that is responsible for executing the predefined control loops and, components that are part of the management architecture level that allow the fish tank operator to visualise sensor data and to set the control loop parameters.

4.5.2 IoT Platform

To implement the server-side component, we choose the WSO2 IOT Server platform. One of the goals of this platform is to implement a scalable server-side IoT Platform. This solution provides capabilities like device and user management, analytics, web portals, support for adopted IoT protocols like MQTT, XMPP and HTTP [20]. Our implementation stores all WSO2 Server related data in a MySQL relational database, but other database types are supported. The WSO2 IoT Server and the MySQL are deployed in two servers provided by the FCT Nova Computing Division.

Both virtual machines were configured during this work. The two servers are exchanging and storing data that raise privacy concerns. To protect data all the data exchanged between servers and communications between servers and clients is protected by Secure Sockets Layer (SSL). The MySQL and WSO2 IOT Server instances are configured to use the certificates provided by the FCT Nova Computing Division.

The architecture for the WSO2 IoT Server platform is presented in Figure 4.8

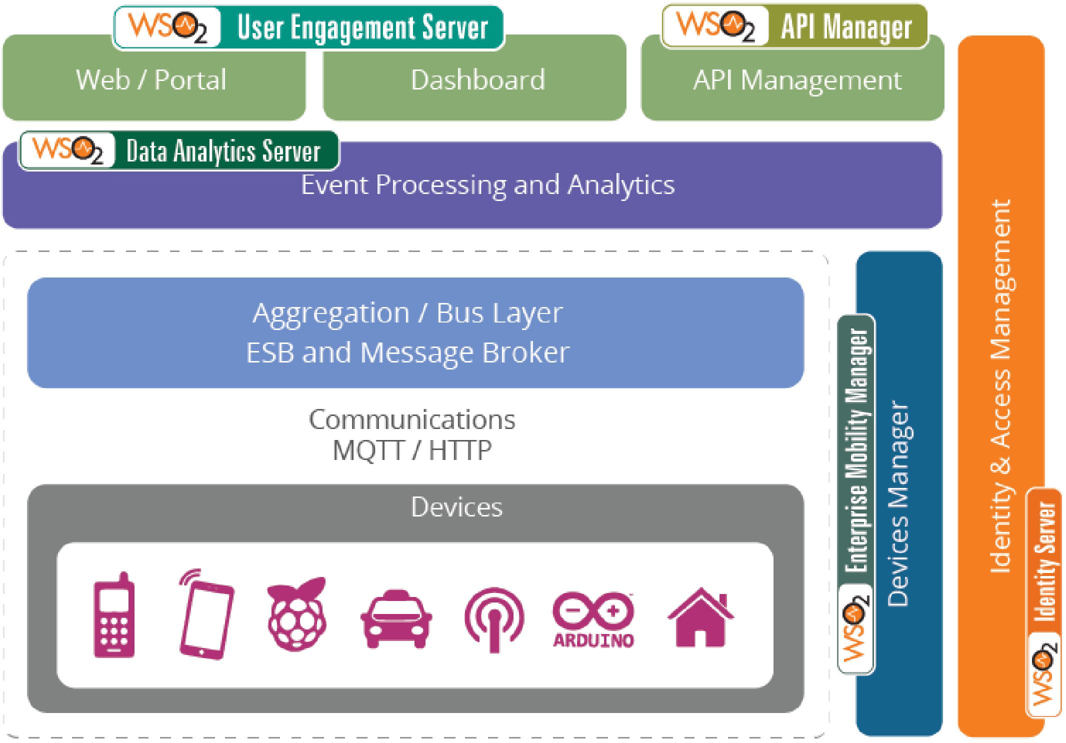

Figure 4.8: WSO2 IOT architecture. Available in the WSO2 documentation [15]

The three main components of this IoT solution are:

- Core - Responsible for managing devices, API, installed applications and support for device plugins and a User Portal. The core device management architecture is available in Figure 4.9.
- Analytics - Processes device gathered data [35]. Different streaming data execution plans can be applied to each event stream.
- Broker - Handles message brokering, enforces MQTT clients authentication configurations and data encryption policies.

Using the exported APIs and developing new carbon applications, IoT server can be extended to support machine learning algorithms or workflows.

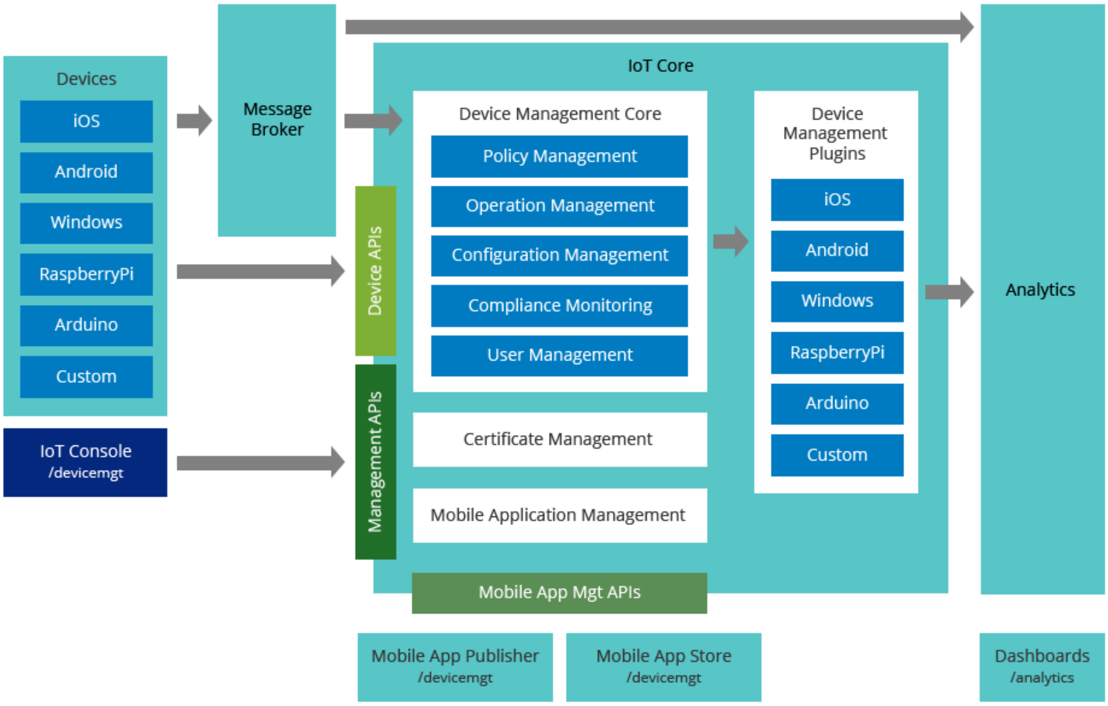

Figure 4.9: WSO2 IOT Core architecture. Available in the WSO2 documentation

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We implemented and deployed device plugins to support the Lifx lights, Ubiquiti power sockets,[6] Estimote beacons,[7] halogen lights, external thermometer, external luminosity and, the Open Aquarium.

The plugins were implemented using the Java programming language and the WSO2 device plugin maven archetype.

A device plugin has five main packages:

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[6] http://www.ubnt.com/ (accessed 25-03-2019)

[7] https://estimote.com/ (accessed 25-03-2019)

- Analytics - Definition of the device data streams and device type related database tables.
- API - Implementation of the device type API definition of the permissions required to access the API endpoints. We support endpoints for access device stats, change a device state (except beacons, outdoors temperature and light sensors), access to the last received state and the download agent operation.
- Plugin - An OSGi bundle that is integrated with the WSO2 Connected Device Framework. The generated artifacts allow the integration with the WSO2 IoT Core Component.
- UI - Implementation of User interfaces that provide real-time data visualisation, ranged data visualisation and general device type information.
- Feature - Definition of device type data sources, an optional agent implementation can be included.

Once the device plugin is deployed to WSO2 IoT Server instance, a device is identified by its device identification alphanumeric string. When the building administrator adds a sensor or actuator to the IoT Server instance, the server replies with a file containing:

- The device identication alphanumeric string.
- The user defined device name.
- The device type.
- Message Broker MQTT and Hyper Text Transfer Protocol Secure (HTTPS) endpoints.
- Authentication method that the agents must use when initiating communication with the server. All the implemented devices type agents use OAuth2 as their authentication method and communicate with the WSO2 Message Broker using the MQTT protocol.
- The OAuth2 authentication and refresh tokens. The default validity period for the authentication and validation tokens is one hour and two weeks respectively. All implemented software agents refresh the authentication tokens every 55 minutes. The renewal is done by calling the available WSO2 Identity Manager API endpoint and providing the refresh token. The server replies with new authentication and refresh tokens.

The device information files generated by Lifx, Ubiquity power socket and halogen lights and beacons plugins, include additional information necessary to the software agents to achieve their goals. The Lifx agent adds the Lifx light system identification string that identifies the light in the Lifx API and the authentication token that the agent must provide when invoking the Lifx API endpoints. The power sockets file must include the power socket local Internet Protocol (IP) address and the socket number. The beacon information has to include the Universally Unique Identifier (UUID) that is broadcasted to allow the software agent to identify the sender of the Bluetooth packet. The halogen light information files contain information about the room light position.

The devices can be added to the system by invoking the device APIs implemented during this work or by using the developed user interfaces. Figure 4.10 presents the user interface where the add device operation starts.

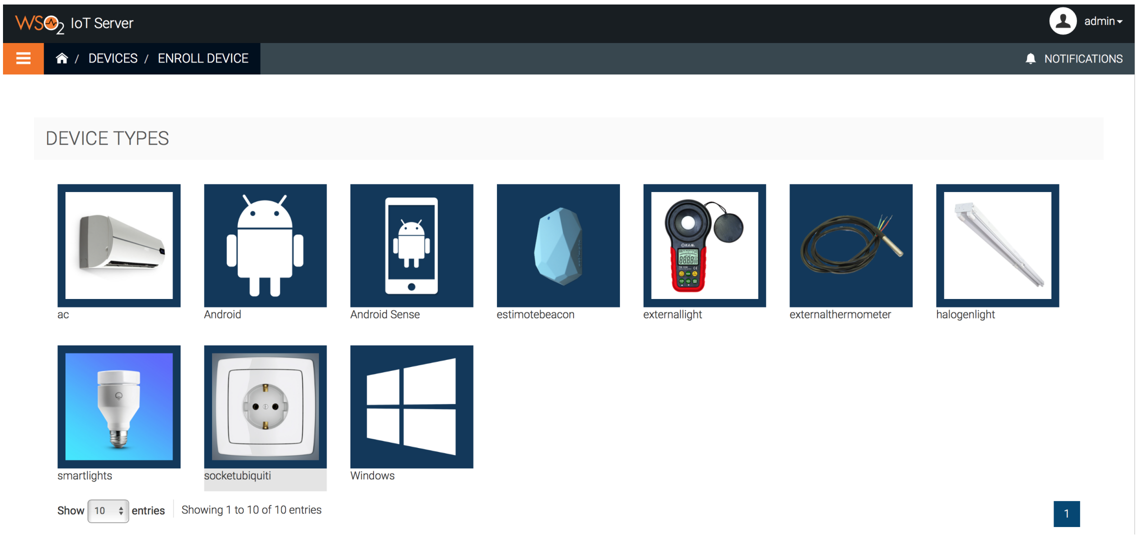

Figure 4.10: User interface provided to initiate the add device operation

For the purpose of simulating human participation as a sensor or an actuator in a BAS, WSO2 Analytics Server provides a feature that simulates data from the configured event streaming data sources. This data can be randomly generated by the server or having as its source a file produced by a simulation tool. This feature allows us to test complicated scenarios that are difficult to reproduce and check if the controller responds with expected behaviour. If the system does not behave as expected, we can modify the system and test the system again with the previous input data.

Considering the three level architecture presented in Chapter 2, section 2.1.3, the WSO2 IOT Server platform has components that are part of management level and other components that are part of the automation level. The WSO2 Analytics server and components that provide user interfaces for data visualisation or platform management are part of the management architecture level. Components responsible for real-time analytics and complex event processing are part of the automation level.

For the context of this work, the IoT Server is already a valuable tool since it provides us with the possibility to detect human involvement in 2 roles of the CPS feedback loop. The human can perform the role of supervisory control. Using the device type real-time interfaces; the user has access to data that is sent from the agents to the server. An example of a power socket analytics interface is presented in Figure 4.11.

Figure 4.11: Real-time power consumption user interface

He can then make decisions regarding the data and emit commands via the device type control interface that will change the device state. The following operations for each device type are available:

- Lifx Lights - Change brightness in the zero to hundred range, alter the current colour and set the on or off states.
- Ubiquiti power sockets - Set the enable or disabled state.
- Halogen lights - Turn on or off the light.
- Air conditioning - Set the desired temperature, select the cool, heat, auto, or econo cool operation modes. The econo cool mode claims that the temperature can be two degrees Celsius higher than the user selected temperature without loss of room users comfort. This goal adjusts the airflow to reach its goal. It is also possible to set the on or off states.

The available control user interfaces invoke the device plugin APIs endpoints. Due to time constraints, the user is required to input a string to change the device feature. In the future new user interfaces should be deployed so that it wouldn't be required from users a text protocol to change a device feature state. One possible enhancement would be the availability of a visual colour picker interface that users could use to alter the lights colours. Figure 4.12 presents the currently available user interface to control the Lifx light feature state.

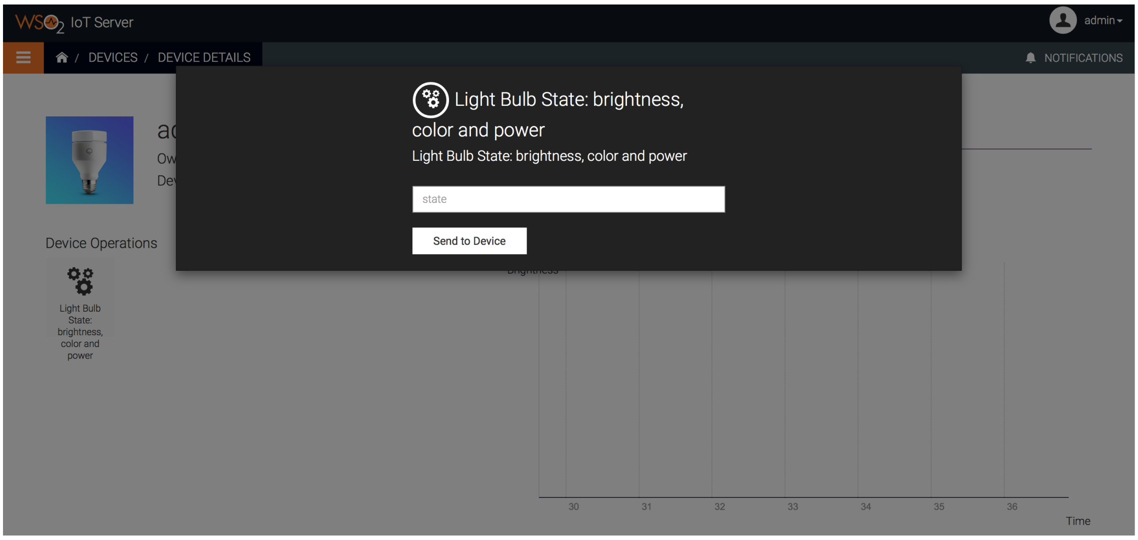

Figure 4.12: Lifx light control user interface

4.5.3 Agents

Agents play a major role in our solution. They are responsible for preprocessing data gathered from the devices and if the decision is made that the data is relevant, the information is sent by the agent to WSO2 IoT Server. Since the storage resources allocated to the project are limited, it is crucial to reduce the quantity of stored data without losing relevant information. Agents also are responsible for applying MQTT commands issued by the IoT Server, seeking a change in the state of the device. This approach hides device hardware details from the server. Seven agents were implemented and deployed:

- Lights - Using the Lifx LAN Protocol[8], the agent retrieves and changes the Lifx light bulbs features state. Data is sent to the server if there is a change in the brightness, colour or if the light is turned on or off. The agent was implemented using the Java programming language and the agent program class diagram[9] is available in this work's Github repository.

- Air Conditioning - Since the AC unit installed in the laboratory can only be controlled using the supplied infrared remote control, we implemented an automated remote control using a Raspberry Pi and Energenie Pi-Mote Infrared Control Board. The hardware setup is presented in Figure 4.13. The infrared board has two led emitters available that are associated with two Raspberry General Purpose Input Output (GPIO) pins. Our first approach was to clone the original signals emitted by the Mitsubishi infrared remote. We observed that each command generated a 34 bytes signal, and only a few bytes changed between similar commands. This indicated that each command includes a setting value for all the available features and

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[8] https://lan.developer.lifx.com/ (accessed 25-03-2019)

[9] https://github.com/jmpcambeiro/fctthesis/blob/master/lifx_agent_classdiagram.png (accessed 25-03-2019)

thus invalidated our initial approach because of the need for a command database that supports all the possible combinations of the available feature values. The HVAC-IR-Control [10] library supports different AC types of equipment from different manufacturers. It was only necessary to adapt the Mitsubishi protocol related code to support the Mitsubishi model MSZ-HJ50VA installed in the laboratory. Only the operating modes and van parts of the protocol differ from the original library, and the necessary signal codes were found by analysing the signals emitted from the vendors remote. The agent was implemented using the Python language, and it is possible to receive server commands to set the AC equipment operating mode, toggle the power on or off, select the desired temperature and change the van settings.

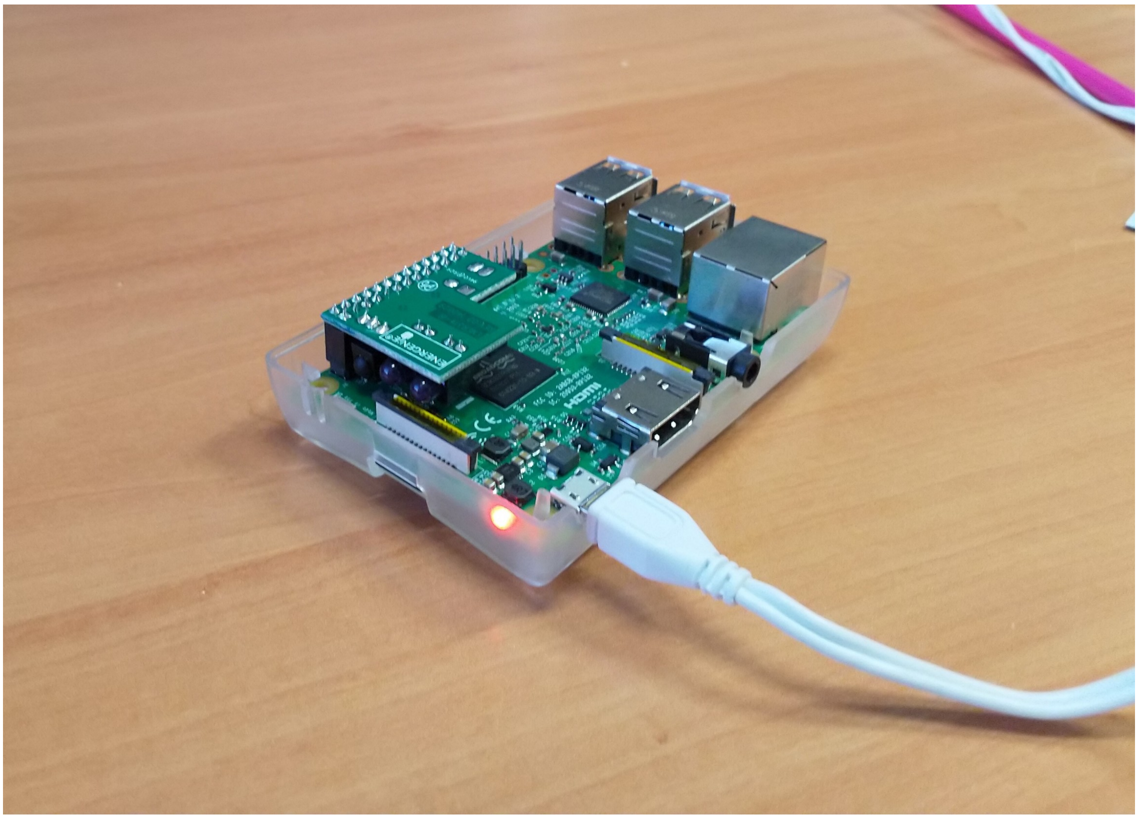

Figure 4.13: Air conditioning agent hardware solution

- Power Sockets - using the Ubiquiti REST Application Programming Interface (API), the agent retrieves and changes the power socket state. Data is sent to the server if there is a variation of twenty percent in power consumption or current, or if the socket is disabled or enabled. The agent program is implemented in the Java programming language and the agent's class diagram[11] is available in this work's

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[10] https://github.com/r45635/HVAC-IR-Control/ (accessed 25-03-2019)

[11] https://github.com/jmpcambeiro/fctthesis/blob/master/powersocket_agentclass_diagram.png (accessed 25-03-2019)

Github repository.

- Halogen lights - It was necessary to adapt the electrical board configuration to automate the halogen lights control. Initially, four mechanical switches controlled the lights. With the support of the Faculty's Technical Department, all the necessary electrical board circuits adaptions were made. A Raspberry Pi with a relay board presented in Figure 4.14 is used to switch on or off the lights. Each relay is associated with a Raspberry General Purpose Input Output pin (GPIO) and its state changes by altering the pin activation status. For safety reasons, all the relays are configured to be normally open. This allows the occupants to change the lights state using the physical switches during the periods where the Smartlab control system is not operating. The agent is implemented in Python and receives from the server the commands that change the lights operating status.

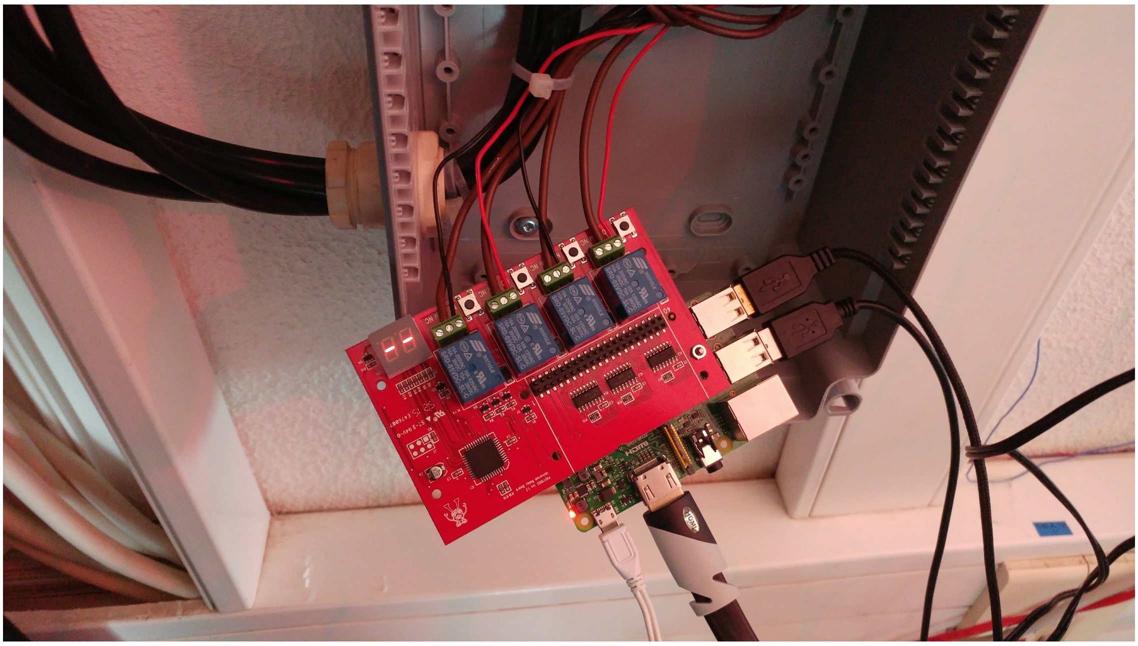

Figure 4.14: Halogen lights agent hardware solution

- Beacons - The Estimote beacons are configured to broadcast a BLE [17] telemetry packet every ten seconds. This packet contains information about the current ambient temperature, light level, accelerometer sensor data, magnetometer and, battery status. The agent was implemented using the Node.js programming language and the BLE central module Bleno [12]. The agent sends data to the server if a variation of 0.250 degrees Celsius is detected, if a change of twenty percent in the light level exists or if the battery level changes.
- Outdoors Temperature - The DS18B20 temperature sensor is used to collect the outdoors temperature data, and the sensor is connected to a Raspberry Pi. The

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[12] https://github.com/noble/bleno (accessed 25-03-2019)

sensor is waterproof and is deployed outside of one laboratory windows where there is no direct sunlight exposition. The hardware setup is presented in Figure 4.15. The agent publishes the last temperature reading data to the event stream if a variation of 0.250 degrees Celsius is detected. The agent senses the outdoors temperature every thirty seconds. The agent is implemented using the Python programming language. The hardware setup is presented in Figure 4.15

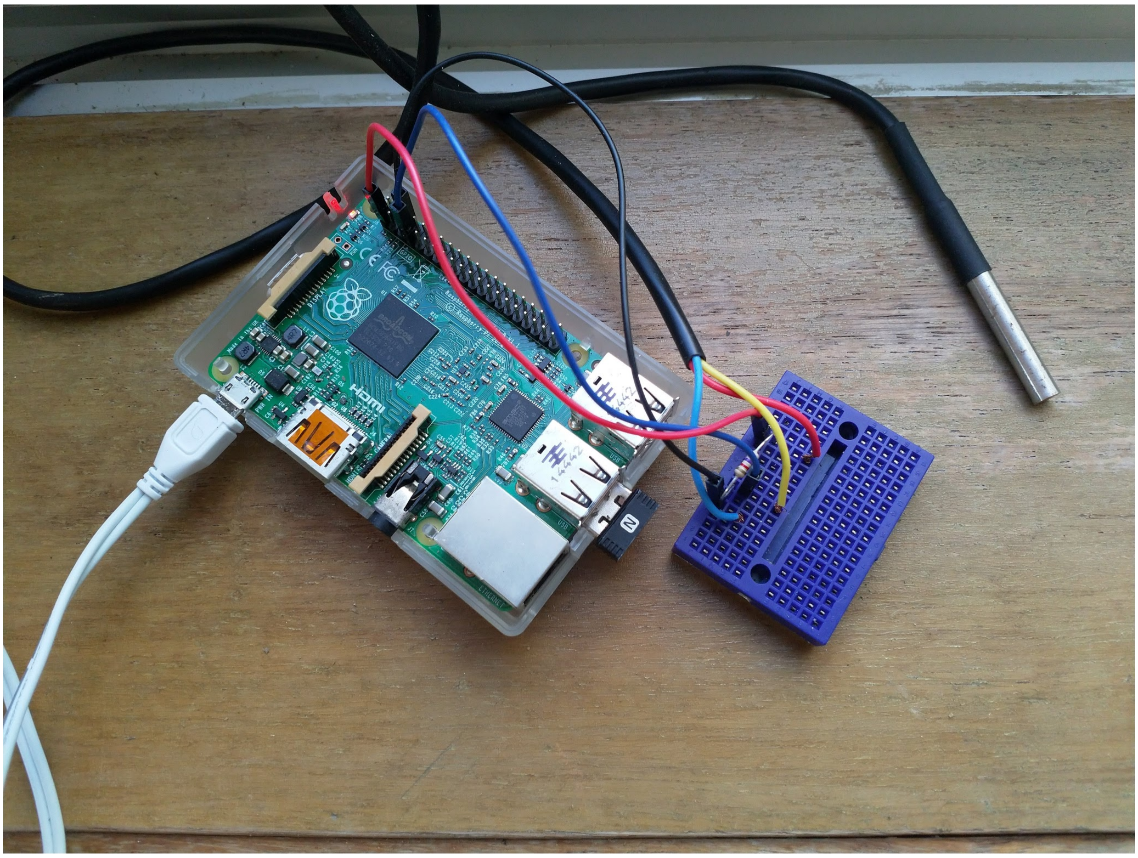

Figure 4.15: Outdoor temperature agent hardware setup

- Outdoors Luminosity - It was necessary for soldering work to assemble the TSL2561 sensor. The hardware setup is presented in figure 4.16. The luminosity sensor is connected to a Raspberry Pi. The sensor is able to measure visible light levels between zero and forty thousand lux. If the luminosity levels exceed the maximum supported light level the sensor overflows and the recorded value is not valid. In this situation, the adopted strategy is to push a forty thousand lux reading into the sensor data stream because we can assume the luminosity level is above the operating range maximum bound. The agent publishes the last visible light reading to the event stream if a variation of 15 lux is detected. The agent is implemented in the Python programming language. The agent senses the outdoors luminosity every thirty seconds. The sensor is placed inside the building and facing one of the laboratory windows. The hardware setup is presented in Figure 4.16

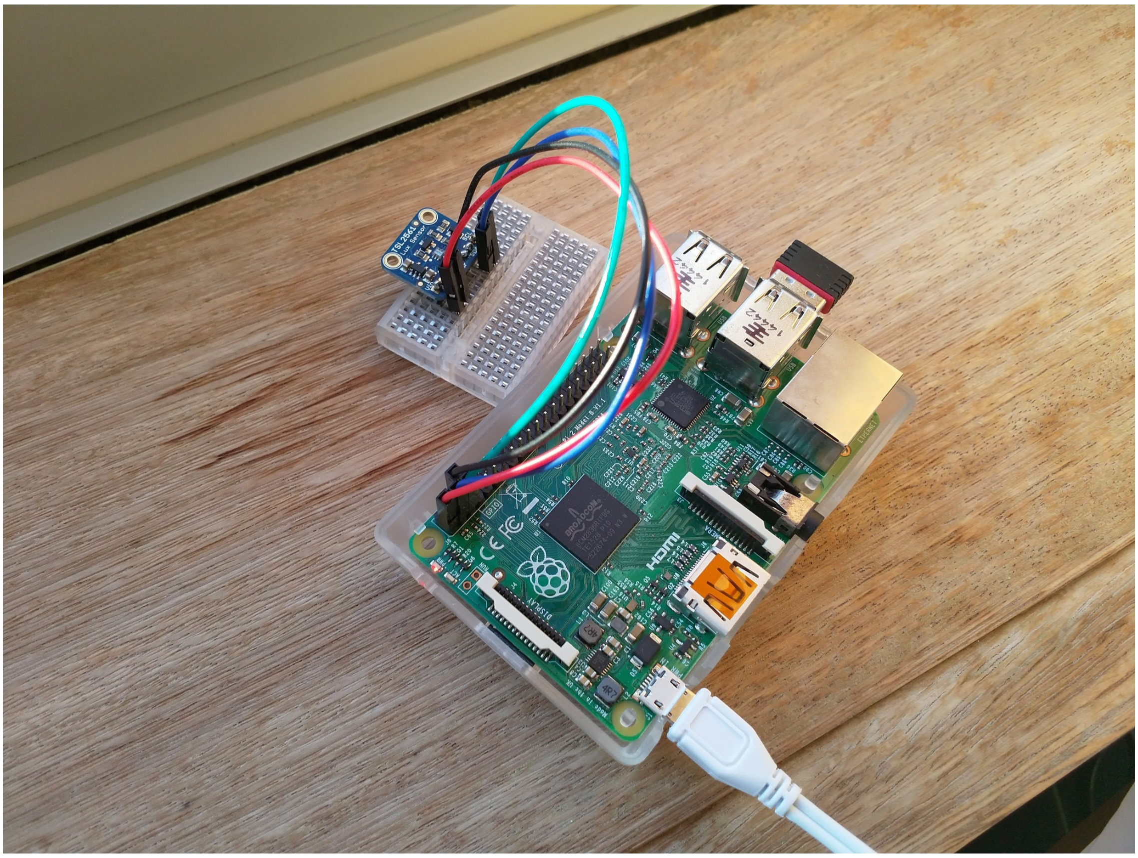

Figure 4.16: Outdoor Luminosity agent hardware setup

- Aquarium - The Open Aquarium solution supports only the Arduino Uno board. The board has 32KB of flash memory, 2KB of SRAM and 1KB EEPROM. To implement the agent Arduino program it was necessary to include the Open Aquarium, the ArduinoJson, the arduino-mqtt and the Waspmote WIFI libraries. The board available memory is not sufficient to upload all the necessary libraries and the Arduino program. The adopted solution is to assign different agent components to a Raspberry Pi and an Arduino Uno board. The Arduino board and the Raspberry Pi are connected by a USB cable and communicate using a serial port. The two devices follow a client-server architecture, with the Arduino program servicing the Raspberry Pi program requests. The handling of MQTT topics and messages, the sensor data preprocessing and publishing data to the server's event streams are all tasks performed by the Raspberry program. The Arduino program includes the Open Aquarium library and performs all the operations that query and change the Aquarium state. To better illustrate the communication between the IoT platform and the aquarium agent we present in figure 4.17 the messages exchanged by the change light level command issued by the IoT platform. The refreshing aquarium state task is executed every thirty seconds by the Raspberry Pi agent program. The IoT platform receives updates regarding the water temperature and the water's pH and conductivity levels. The control algorithm is able to change the aquarium state by changing the light levels, activating the fish feeder and setting on or off the water ventilator.

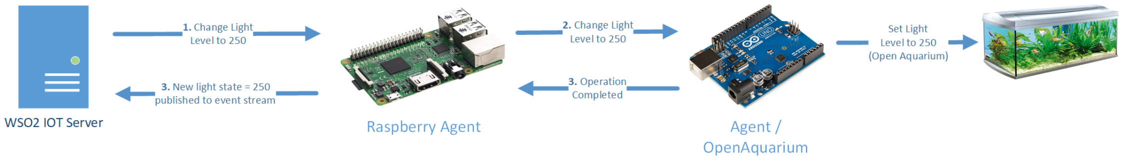

Figure 4.17: Messages exchanged during the aquarium change light command

An analysis of the available sensors and actuators in the market was made for the halogen, outdoors temperature and luminosity agents. Since we are dealing with retrofitting scenario our choice relied on cheap IoT solutions that required minimal changes in the available building configuration. All the agents were assembled and configured during this work.

Considering the three level architecture presented in Chapter 2 section 2.1.3, agents are part of the automation level as they are responsible for pre-processing sensor collected data and sending settings defined at the management level to the physical plant actuators.

4.6 Deployment

The deployment process started with the placement of the available sensors and actuators. The Smartlab has as one of its primary goals the availability of the best temperature and luminosity conditions to laboratory users. For this purpose, sensors and actuators were associated with each available workstation. Firstly, we defined the workstation numbering scheme presented in Figure 4.18. We will follow the same numbering scheme for the laboratory users. As an example: user one works on Workstation one and user eight works on Workstation eight.

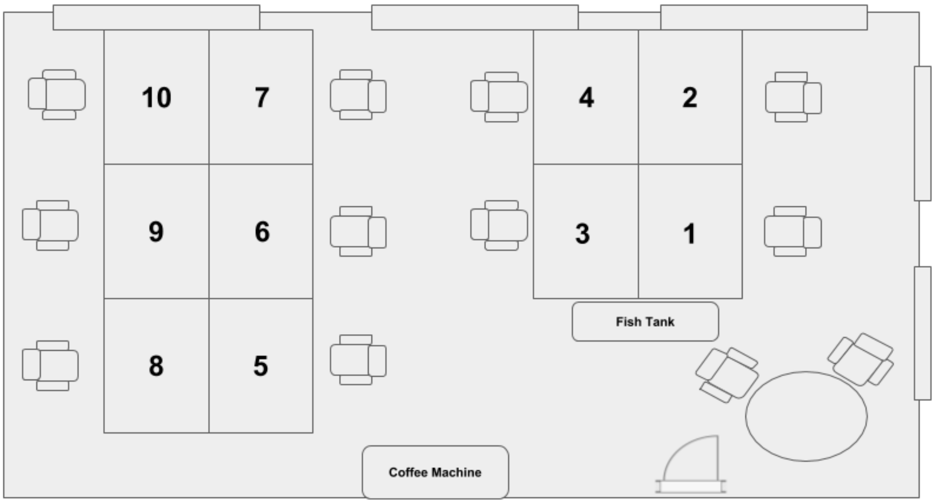

Figure 4.18: Workstation numbering scheme

Each workstation is associated with an Estimote beacon that allows the measurement of the light and temperature conditions. The beacons are configured to operate in the Proximity mode presented in section 4.3.2 and each beacon is configured to broadcast a unique zone identified by the workstation number. The radius for every region is set to two meters. The region entrance and exit events allow us to monitor when users are working at their assigned workstations. The other eight beacons are deployed at the laboratory walls, one meter and sixty centimetres high. These beacons are part of the Estimote Indoor Location system and provide us with valuable data regarding the temperature and light conditions that change during the day.

The number of available Lifx lights is not sufficient to assign a light to every workstation. Workstations two, six, seven, eight and ten have a Lifx light associated. The remaining light is deployed near the aquarium and is used to provide alerts to users that aquarium requires maintenance.

Every workstation has assigned three power sockets. With this configuration it is possible to monitor the energy consumption related to the user laptop, an external display and other devices that the users may bring to the laboratory. During the execution timeframe of this work, the workstation one was vacant, and the decision was made to assign the three available power sockets to Open Aquarium solution. This decision allows the analysis of the Open Aquarium energy consumption patterns.

The following sixty devices were deployed:

- One outdoors temperature sensor.
- One outdoors luminosity sensor.
- Eighteen Estimote beacons.
- Five Ubiquiti power strips, with a total of thirty power sockets available. Each power socket is controlled independently of the other power strip's sockets.
- Six Lifx lights.
- Four halogen light rows. Each light row has 4 halogen lights that can not be controlled independently.

The deployed Smartlab setup is described in figure 4.19.

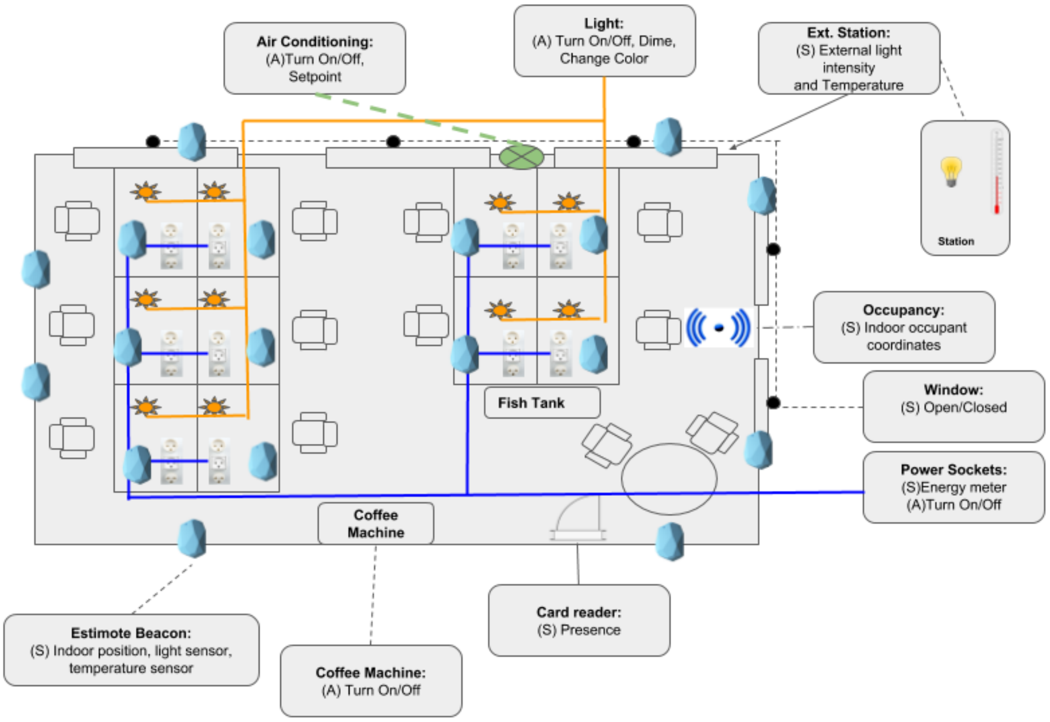

Figure 4.19: Smartlab setup

During the system design stage, the following network requirements were identified that the available Wifi Eduroam network does not fulfil:

- The underlying network must support Transmission Control Protocol (TCP) and connections between different network devices.

- The Lifx agent has to be given access to the Lifx API endpoints. Network clients connect to Eduroam network cannot reach the Lifx API endpoints.

- The solution administrator has to be given network administrative permissions to perform Dynamic Host Configuration Protocol (DHCP) address reservations. Having DHCP and Domain Name System (DNS) administration rights facilitates the introduction of new devices and network reconfiguration operations.

A Raspberry Pie was configured to serve as the laboratory network router and as a wireless access point. The Raspberry pie Local Area Network (LAN) port is connected to the Faculty's laboratories wired network and network clients connect to the network by joining the available Smartlab wireless network. As we are dealing with sensitive data that could endanger the users' privacy, the network authentication method is WPA2-Personal, and communications are encrypted using the Advanced Encryption Standard (AES) encryption method. Restricting network access is also essential as a connected device would have access to actuating devices. During the deployment process, a major vulnerability was detected regarding the Ubiquiti power sockets API protocol. While performing network load tests using a packet sniffer with the objective to verify if the Raspberry Pie could cope all the generated network traffic, we detected that the administrative token is exchanged unencrypted between the power strips HTTP server and the power agent described in section 2.1.4. This is part of the Ubiquiti provided protocol, and as such, we had no alternative to solve this problem. The chosen approach was to rely solely on restrict network access to wireless clients and to connect the Power Strips to the network using the network radio. If an unauthorised client gets access to this token, it would provide him full power strip control. In a production environment or if the power strips are connected using the LAN port, the power agent device and the power strips should join an isolated Virtual Lan (VLAN).

4.7 Human-BAS interaction with the system

Since we will evaluate human participation as sensors or actuators in the feedback loop, we argue that having other interface types (fig. 4.20) than a web page available will increase user satisfaction with the system. Besides the already available portal, an Android application and voice commands for Lifx lights control are also available. Using the mobile application users able to monitor the laboratory equipment for which they possess authorisation.

Figure 4.20: System interfaces available to the occupants

4.7.1 Mobile Application

A mobile application was developed to give a more natural and more intuitive user experience than the WSO2 IoT Server portal that can be accessed by a web browser. The web browser interface requires from users that are looking for data related with their workstation, the login on the platform and the navigation from several web pages to consult the sensor values.

All the Smartlab users currently own an Android[13] smartphone, and as such our, mobile platform choice was restricted to the Android operating system. The application is implemented in the Kotlin[14] programming language and relies on the following Android Architecture Components[15]:

- ViewModel - Manages and stores the data that is presented in the application user interfaces. This architecture component is aware of the Android application lifecycles[16] and avoids the regeneration of already fetched data on detected system configuration changes.

- Room - the application uses the Android embedded SQLite database. The users, sensors, laboratory, workstations and tasks information is stored in the database. The Room architectural component provides a mapping between SQL tables and Java class objects.

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[13] https://www.android.com (accessed 25-03-2019)
[14] https://kotlinlang.org (accessed 25-03-2019)
[15] https://developer.android.com/topic/libraries/architecture (accessed 25-03-2019)
[16] https://developer.android.com/guide/components/activities/activity-lifecycle (accessed 25-03-2019)

- LiveData - is an observable data holder class. LiveData like Room is aware of the application's lifecycle. Data observers like user interfaces components are notified when the data fetched from the database is updated. This is an important feature that helps to reduce memory leaks, handles system configuration changes and ensure that data presented to the user is always up to date.

The use of Android Architecture components improves the maintainability of the application as these components are updated regularly to support the underlying operating system updates. It also reduces the application energy consumption because of the reduction of the number of data operation retrievals. The application is supported on devices running Android API 22 or a higher version number and the smartphone's Bluetooth hardware has be compliant with Bluetooth versions four or five.

System users credentials are provided to the Smartlab's users. The users' institutional email assigned as their username and an alphanumeric password is provided to them. All the users' credentials and the JSON Web Token (JWT) tokens that the application presents to the Smartlab controller's API to authenticate the required operations are stored in the Android keystore system. This presents a challenge to attackers trying to access the users' credentials with the objective to access the Smartlab system or mask their system operations. After the user completes the login operation successfully the application navigates to the home interface presented in Figure 4.21.

Users can check the temperature and light conditions at their workstation and laboratory outdoors. This information is updated by a background task that invokes the server components REST endpoints to keep up to date the acquired sensor data. This task is executed every 30 seconds while the interface is in a visible state. The Volley[17] library is used to optimize the network task's energy consumption.

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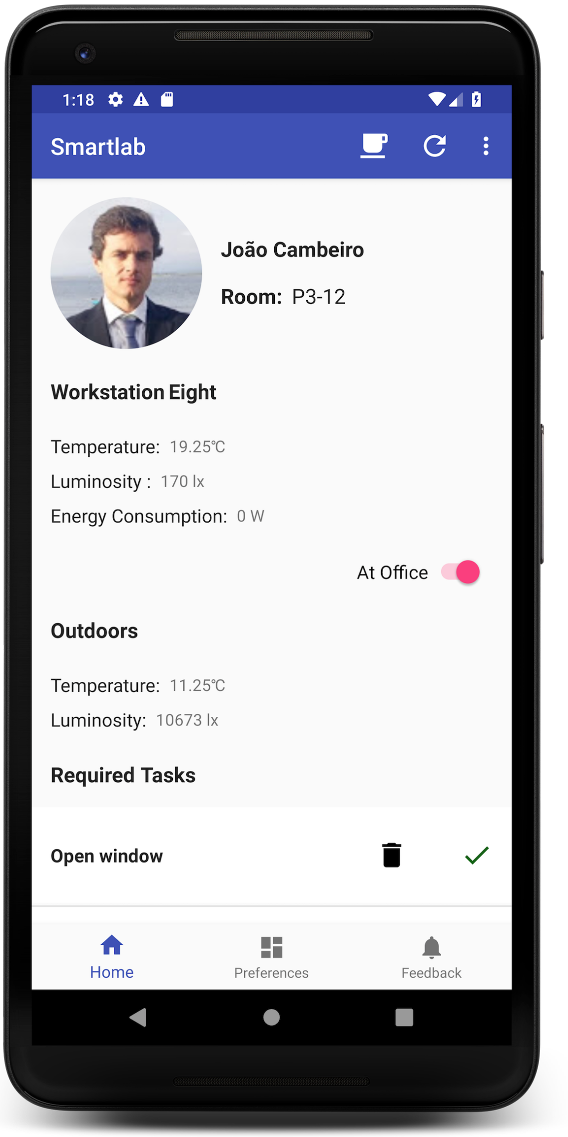
[17] https://github.com/google/volley (accessed 25-03-2019)



João Cambeiro

Room: P3-12

Workstation Eight

Temperature: 19.25℃
Luminosity : 170 lx
Energy Consumption: 0 W

Outdoors

Temperature: 11.25℃
Luminosity: 10673 lx

Required Tasks

Open window

Figure 4.21: Home interface - User related data is presented

The information if the Smartlab system considers the users present at their workstation is also available. This information is essential because, in two testing scenarios that we will present in section 5.1, the system will react to arrival and exit events, activating and deactivating the Smartlab actuators presented in sections 4.4 and 4.3. The Estimote Proximity mode presented in section 4.3.2 is implemented and the application reacts to arrival and departure events to the area defined by workstation associated beacon. When an event is triggered the application invokes the appropriate Smartlab's controller API endpoints.

In figure 4.22 is presented the activity diagram that describes the system behaviour when users arrive at their workstations. In section 76 we will present in more detail the BAS controller.

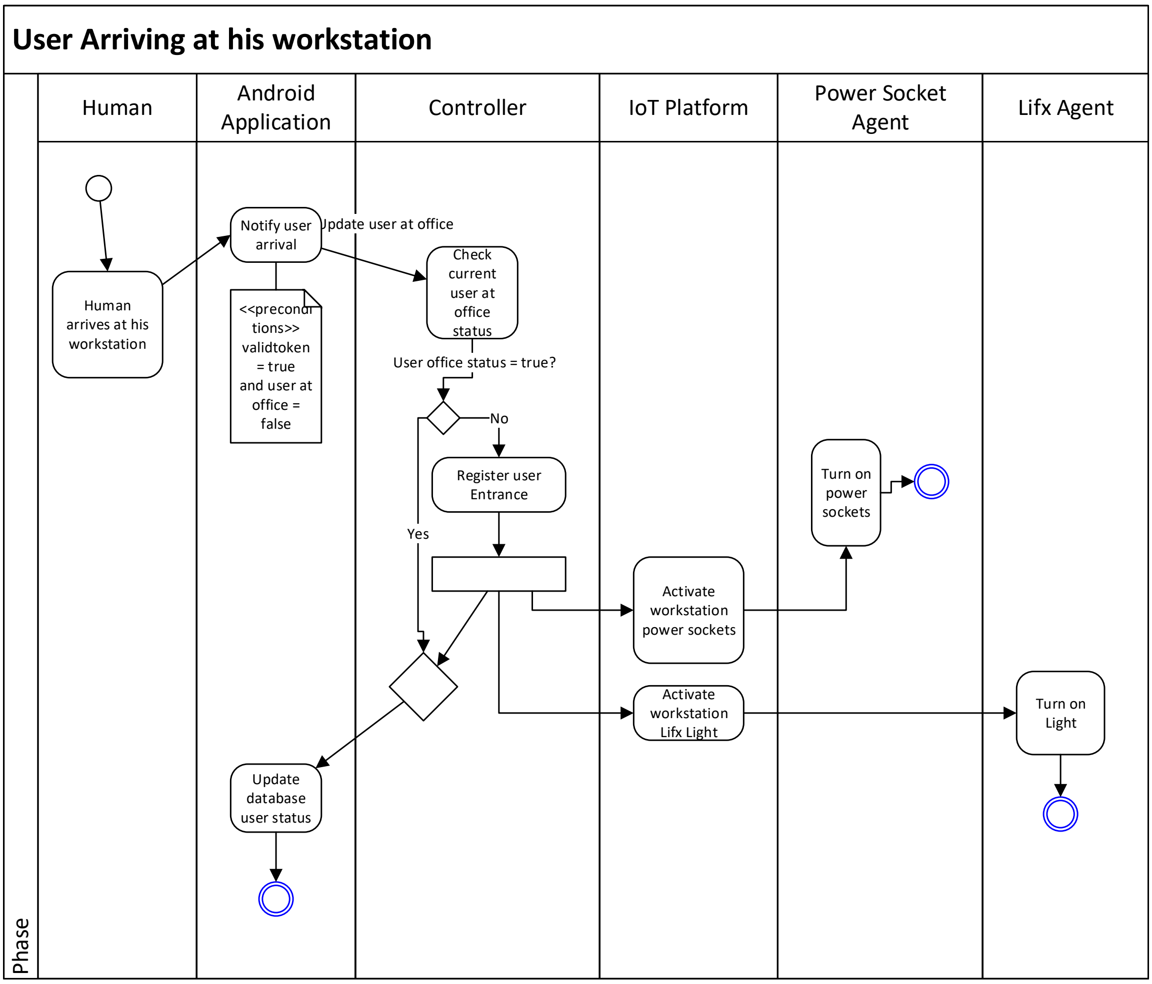
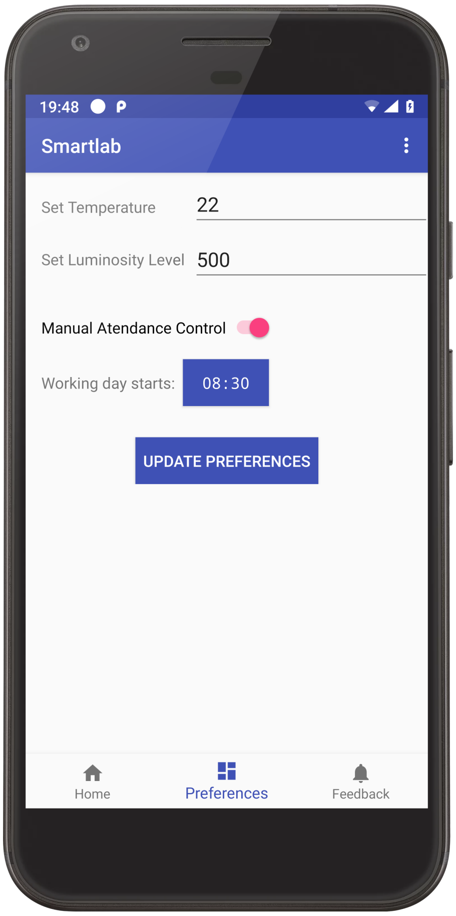


Figure 4.22: Home interface - User related data is presented

The tasks that the Smartlab's controller requires from the user are presented at the scrollable interface's bottom. This is an important feature that will allow the use of humans as system actuators. The users can notify the system controller that a task has been completed by clicking check icon button.

One of the BAS goals is to improve the users' satisfaction regarding the environmental conditions at their workplace. To achieve this goal the system needs as input the users' input regarding their environmental conditions preferences.The preferences user interface presented in Figure 4.23 provides the opportunity for users to input their preferences regarding light and temperature conditions.



Set Temperature 22

Set Luminosity Level 500

Manual Atendance Control ●

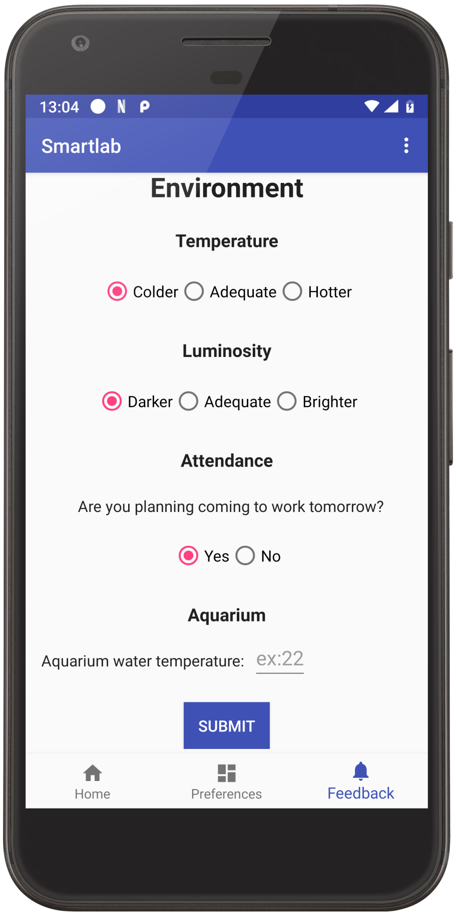
Working day starts: 08:30

Figure 4.23: Preferences - User can indicate the preferred environmental conditions

Users can also change choose to be their responsibility to signal the BAS controller when they are present at their workstation. The activation of this setting stops the application's use of Estimote location system. We included this setting to achieve a higher system's resiliency in situations where indoor location malfunctions due to problems like beacons running out of battery or the access of the user's smartphone Bluetooth radio is not possible.

Users can also define the expected time of arrival at the office. This information will provide the ability for the BAS controller to prepare the office environmental conditions and to schedule the necessary tasks that are performed by the users.

In the scenarios where the Smartlab's controller is active, the users' assessment of the provided working conditions is an essential factor in the control algorithm. By delivering evaluations regarding the working conditions, the users are performing the CPS feedback loop's sensor role. Users can input their assessment using the feedback interface that is presented in Figure 4.24. Users can also provide the information if they are expecting to work at the lab the next day. This input is essential in scenarios where the system has the objective to provide the users preferred environmental conditions at the users time of arrival to the office. We present an example of in two testing scenarios in chapter 5.



Environment

Temperature

● Colder ○ Adequate ○ Hotter

Luminosity

● Darker ○ Adequate ○ Brighter

Attendance

Are you planning coming to work tomorrow?

● Yes ○ No

Aquarium

Aquarium water temperature: ex:22

Figure 4.24: Feedback - Users can provide feedback to the Smartlab's controller

4.7.2 Voice Interaction

To support voice interactions between the laboratory users and the Smartlab we implemented a voice-enabled assistant. The voice interaction method requires from user fewer steps to interact with the BAS comparing to the mobile application presented in the previous section. We choose the Google Assistant [18] platform because it includes natural language, speech recognition and voice synthesis support in various languages. The Google assistant is already supported in multiple hardware devices like smart speakers, headphones, TVs or IoT devices. To interact with the assistant, users can use the Nordic Thingy multi-sensor platform [19] presented in figure 4.25. Nordic provides developers with the necessary software[20] to create a Google Assistant solution based on one Thingy and one Raspberry Pie.

The Smartab users can initiate dialogues with the assistant by pressing the Thingy's button and saying "OK Google, talk with watts lab".

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[18] https://assistant.google.com/ (accessed 25-03-2019)

[19] https://www.nordicsemi.com/Software-and-Tools/Development-Kits/Nordic-Thingy-52 (accessed 25-03-2019)

[20] https://github.com/NordicPlayground/Nordic-Thingy52-Nodejs/blob/master/GOOGLE_ASSISTANT.md (accessed 25-03-2019)

At the moment users can:

- Switch their workstation LED light on or off.
- Change their LED light's brightness.
- Ask for their current total energy consumption.
- Ask for the current total Smartlab energy consumption.

The users' voice commands are not required to comply with rigid grammar style commands. We created Google DialogFlow[21] intents to support the available actions. For each intent, the speech recognition engine is trained with variations of the expected user action command.

To fulfil the users' commands, we implemented Google Cloud Firebase functions [22] that fetch and update the necessary information from the WSO2 IoT Server REST endpoints and the Efergy energy monitoring API.

Figure 4.25: Nordic Thingy multi-sensor platform

In the future, we intend to extend the available commands set, create a WSO2 device plugin to support the device's sensors array. The room's users will have the possibility to use voice commands or their RFID student card to inform the system when they enter or exit the office. With these two new features, we expect that the BAS will become more resilient to situations where the users' smartphone Estimote indoor location cannot be

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[21] https://dialogflow.com/ (accessed 25-03-2019)

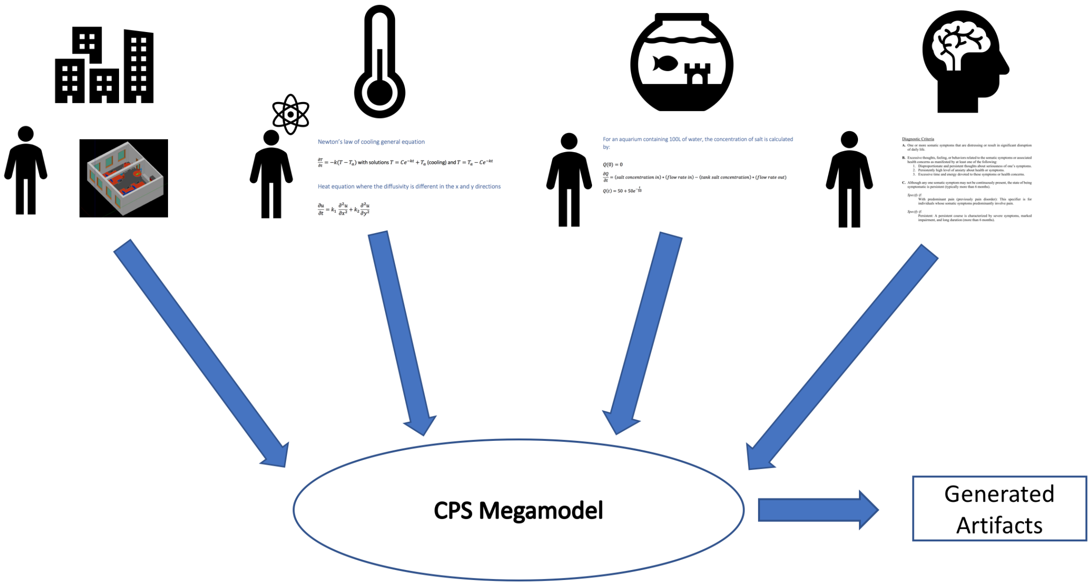
[22] https://firebase.google.com/docs/functions/functions-and-firebase (accessed 25-03-2019)

used. The device's LED can change the presented colour, and this gives us the opportunity to create a colour code that could be used to notify when users have tasks assigned or to provide a visual representation on how environmentally friendly the user is. This way, the user would not have to periodically check the mobile application for pending tasks or how sustainable their current environmentally behaviour is.

4.8 Smartlab Modelling

When modelling a system as the Smartlab case study, BAS developers have to integrate several engineering disciplines. Additionally, as the system considers humans as system components, modelling humans at the appropriate level of abstraction is also necessary. Each of the disciplines involved uses their formalisms, tools and techniques. When creating buildings structural models, structural engineers may use Computer-aided design (CAD) models like the model the we developed and presented in figure 4.2 , when forming the room's thermal models, mechanical engineers may use differential equations, when creating models that describe the aquarium biology, aquarium specialists may use biological models, and when psychologists are modelling human behaviour, they usually use textual models.

Multi-paradigm modelling [43] proposes to model every part of the system explicitly, at the most appropriate levels of abstraction using the most appropriate modelling formalisms.



Newton's law of cooling general equation

$\frac{\partial T}{\partial t} = -k(T - T_a)$ with solutions $T = Ce^{-kt} + T_a$ (cooling) and $T = T_a - Ce^{-kt}$

Heat equation where the diffusivity is different in the x and y directions

$\frac{\partial u}{\partial t} = k_1 \frac{\partial^2 u}{\partial x^2} + k_2 \frac{\partial^2 u}{\partial y^2}$

For an aquarium containing 100L of water, the concentration of salt is calculated by:

$Q(0) = 0$

$\frac{\partial Q}{\partial t} = (salt\ concentration\ in) * (flow\ rate\ in) - (tank\ salt\ concentration) * (flow\ rate\ out)$

$Q(t) = 50 + 50e^{-\frac{t}{50}}$

Diagnostic Criteria

A. One or more somatic symptoms that are distressing or result in significant disruption of daily life.

B. Excessive thoughts, feeling, or behaviors related to the somatic symptoms or associated health concerns as manifested by at least one of the following:
  1. Disproportionate and persistent thoughts about seriousness of one's symptoms.
  2. Persistently high level of anxiety about health or symptoms.
  3. Excessive time and energy devoted to these symptoms or health concerns.

C. Although any one somatic symptom may not be continuously present, the state of being symptomatic is persistent (typically more than 6 months).

Specify if:
With predominant pain (previously pain disorder): This specifier is for individuals whose somatic symptoms predominantly involve pain.

Specify if:
Persistent: A persistent course is characterized by severe symptoms, marked impairment, and long duration (more than 6 months).

Figure 4.26: Smartlab's Multi-Paradigm Modelling Process

In the future, through the development of a Smartlab Domain-Specific language [22] modelling language and using model transformations we will be able to create a system model that unifies the different disciplines involved in the Smartlab domain. From the system model, it will be possible to generate artefacts like the device plugins presented in section 4.5.3, BAS and aquarium controllers, reconfiguration scripts or documentation. The modelling process is described in figure 4.26. During this work, the metamodel[23] of a Domain-Specific language focused on the Smartlab domain has been developed. With the aplication of verification tools and techniques to the language models at system design time, BAS developers will be able to validate design options or to detect configuration problems, before proceeding to the deployment of the system. The language will also be a valuable tool in reconfiguration scenarios where a small change in the system can propagate to various components, and the automated generation and deployment of the updated artefacts will help to reduce errors during the reconfiguration process.

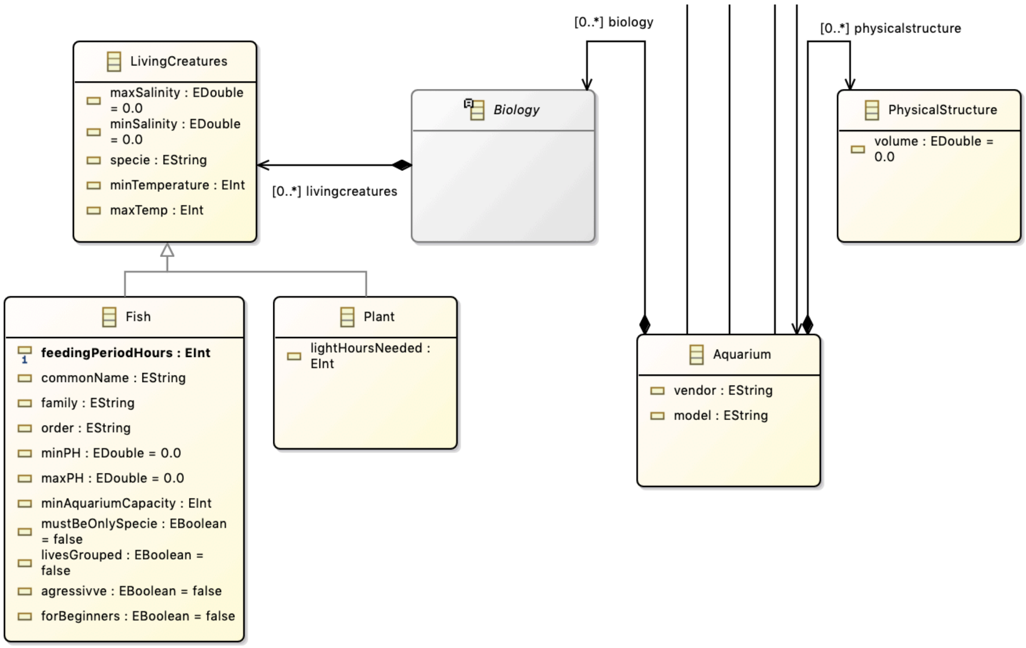


Figure 4.27: Smartlab's meta-model aquarium

To illustrate the unification of the different disciplines involved in the case study CPS, we present in figure 4.27 part of the meta-model related to the aquarium subsystem. When creating a Smartlab model, the system designers define the aquarium structural attributes, the fishes and plants biology and the set of actuators and sensors used by the aquarium's controller to maintain the observed conditions in accordance with the aquarium's requirements.

In the previous sections, we presented different case study components. When implementing a BAS, system designers have to decide which components should be deployed

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[23] https://github.com/jmpcambeiro/fctthesis/blob/master/smartlab_metamodel.png (accessed 25-03-2019)

and for each of those components, the features that should be available. The number of possible feature combinations in systems like the case study that we have implemented is very high. Considering that the available BAS's feature set may change through time and that small differences in the solutions deployed between BASs may exist we also are following the Software Product Line approach [36].

We have developed a feature model[24], and the compacted version is presented in figure 4.28.

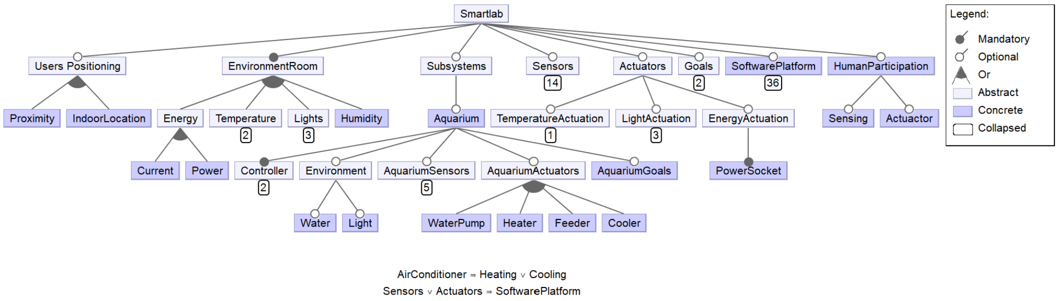

Figure 4.28: Smartlab's feature model - compacted version

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[24] https://github.com/jmpcambeiro/fctthesis/blob/master/featureextended.png (accessed 25-03-2019

CHAPTER 5

EMPIRICAL STUDIES AND DATA COLLECTION

5.1 Description

To provide an answer to the research question presented in section 1.3, it is necessary to conduct at least one year of observation to achieve statistically significant results while covering the four seasons with distinct environment conditions affecting the kind of consumption and occupant's behaviour (as well as their agenda). This study must reflect the laboratory exposure to the different weather seasons and the various occupants' profiles and schedules. We implemented three pilot experiments applied to Smartlab case study presented in section 4 to validate our approach to solve the problem. The data collected will be valuable in understanding the room behaviours and the identification of trends that indicate if in the future the system goals are attainable. The experiments also provided an opportunity to assess the current Smartlab IoT infrastructure's reliability and identify necessary corrections or improvements that need to be applied to the BAS controller.

Humans participate in different roles in the three empirical studies:

- In the first scenario, the human is in control of all the available actuators. In this setup, the human is responsible for maintaining the laboratory appropriated environmental conditions and there is no automation performed by the Smartlab's controller. The system is only gathering the sensor data generated during the empirical study duration.

- In the second scenario, the Smartlab controller is solely responsible for maintaining the environmental conditions. Human participate participate only as part of the CPS plant.

- In the third scenario, the Smartlab controller is operating with the goal of providing the best compromise between the offered environmental conditions and achieving energy savings. The system requires user evaluations regarding the offered environmental conditions. The controller also considers humans as actuators and requires actions from the users that optimize the offered conditions or contribute to the system's energy savings goal. Humans are also required to perform tasks that increase the system's resiliency to sensor failures or miscalibration. In this setup, humans participate in all CPS feedback loop roles presented in section 2.1.

5.2 User surveys

To evaluate the users' satisfaction with the different environmental conditions provided in different scenarios described in the previous section we conducted user surveys at the end of each study.

The three surveys begin with a set of questions that help to characterise the users. Users are asked about their age, educational background and pre-existing health problems. Assessing the occupants' health is important as some eye diseases can influence the users' reliability to perform the light level sensor role. Some physical limitations do not allow the users to deliver as actuators in the CPS feedback loop. Users are then asked to provide assessments regarding the environmental conditions. In the second and third empirical studies, we try to evaluate the impact that an automated system had on their work and if the Smartlab's controller managed to provide adequate temperature and light conditions. Finally, there is an open question where users are invited to give suggestions to improve the system operation.

The received feedback is a valuable input for tuning the Smartlab's controller in future iterations. Combining the received answers with all the available sensor data collected provides an import information source in our effort to identify the difficulties of modelling humans as system components at the abstraction level that is necessary to the Smartlab to operate correctly.

5.3 Smartlab Baseline Power Consumption

The second and third scenarios also required the analysis of the automation infrastructure power consumption. The deployed infrastructure is comprised of:

- One Open Aquarium solution presented in section 4.5.1.
- Five Raspberries Pi executing the device agents described in section 4.5.1.
- Six Lifx lights. It is necessary to measure the power consumption of the Lifx lights even when they are not emitting any light because each light's controller is querying the Lifx API for commands that will result in a change of the light features.

- Five blocks of Ubiquiti power sockets. The Ubiquiti power sockets also consume energy even when don't have any device connected. Each block of sockets is running a controller software, that accepts query and change state commands regarding each of the block's power sockets.

- The Efergy three-phase energy monitoring solution used to monitor the electrical board and the AC unit power consumption.

This study provides the energy costs overhead that result from running a monitoring and actuation solution. Knowing this value is essential to answer if the implementation of this kind of CPSs leads to energy savings.

It was not possible to find the energy consumption values for the servers running the WSO2 IoT Server, MySQL and Smartlab controller. Is our belief as the number of spaces controlled by the system grows, the weight of the server components energy consumption would decrease considering the total energy that is necessary to run the system.

The Smartlab configuration was the following:

- The Open Aquarium solution is running with all the solution's sensors, and actuators enabled.

- The aquarium's water heater controller is set to maintain the water temperature at 24 degrees Celsius.

- All the Ubiquiti power strips are turned on and servicing the power sockets agent requests.

- All the windows are closed, and the blinds are set at half the windows height.

- All the lights are available to change state commands and their brightness is set to zero.

- The coffee machine is turned off.

- The Efergy online energy monitoring solution is running.

5.3.1 Collected Data

During the three days, the Smartlab's infrastructure consumed 8,83 kWh. It is important to note that we do not include the air conditioner unit energy consumption, as this value is tightly coupled to the outdoor temperature and solar exposition that varies during the year. The total energy demand during the test is presented in Figure 5.1.In Figure 5.2 is presented the laboratory energy consumption.

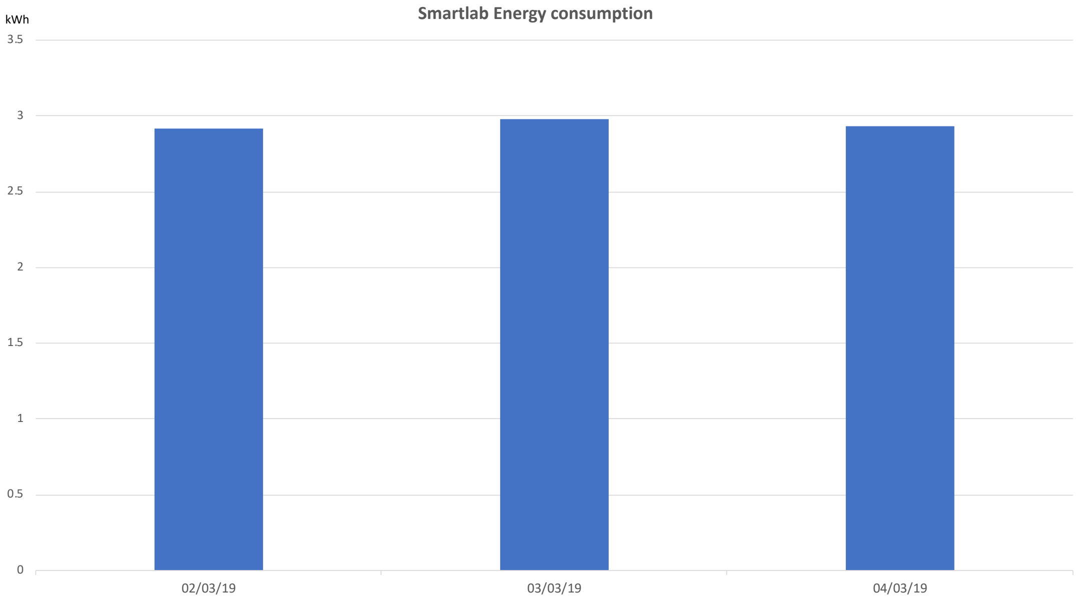

Figure 5.1: Smartlab winter baseline daily energy consumption

The system power consumption variations are mainly a result of the aquarium's water heater. The water heater behaves like a bang-bang controller activating the resistance for short periods. The aquarium heater is connected to one of the monitored power outlets and its energy consumption variation during the test is presented in figure 5.3.

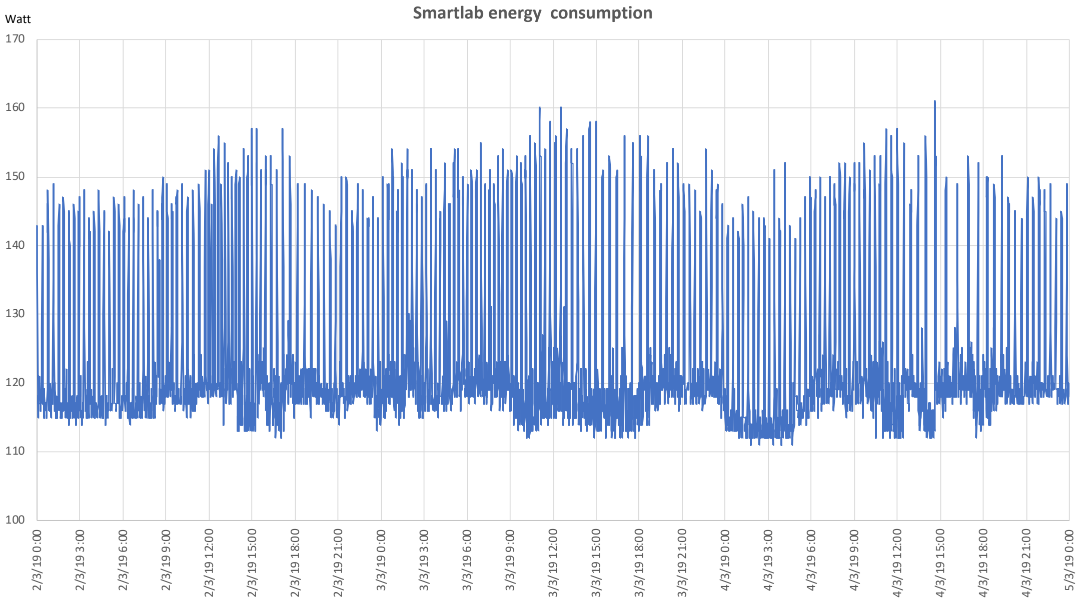

Figure 5.2: Smartlab winter baseline power consumption

An important factor to the total energy consumption is the environmental conditions in which the test took place. As the difference between the defined target aquarium's water temperature and the room temperature increases, the water heater or the water cooler usage increases.

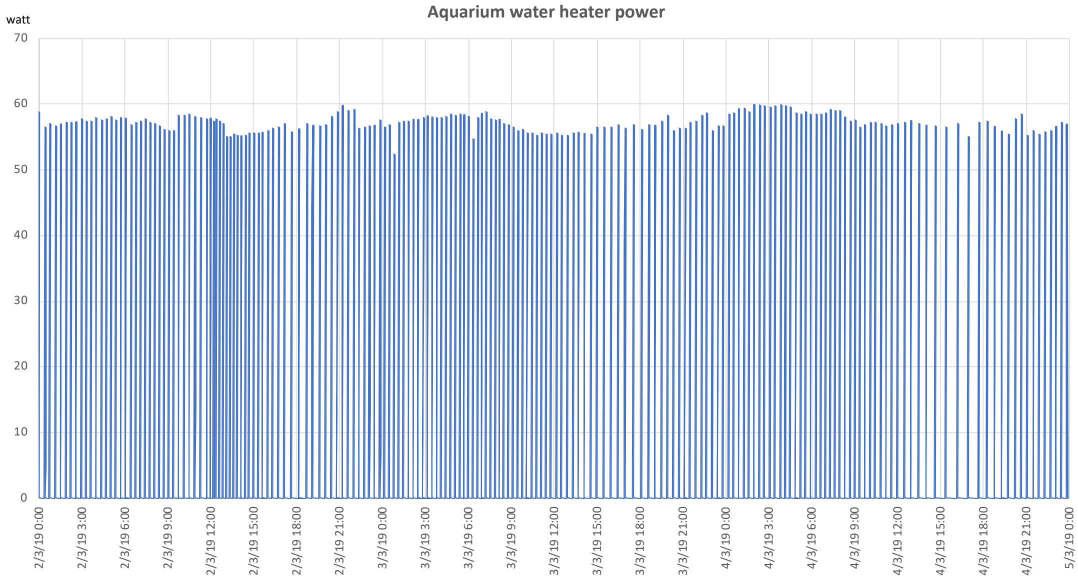

Figure 5.3: Aquarium's water heater power consumption during the test days

During the test days, the outdoor air temperature ranged from 9.25 to 19.19 degrees Celsius, and the indoor temperature ranged from 16.69 to 18.69 degrees Celsius. The outdoor temperature variation is presented in 5.4.

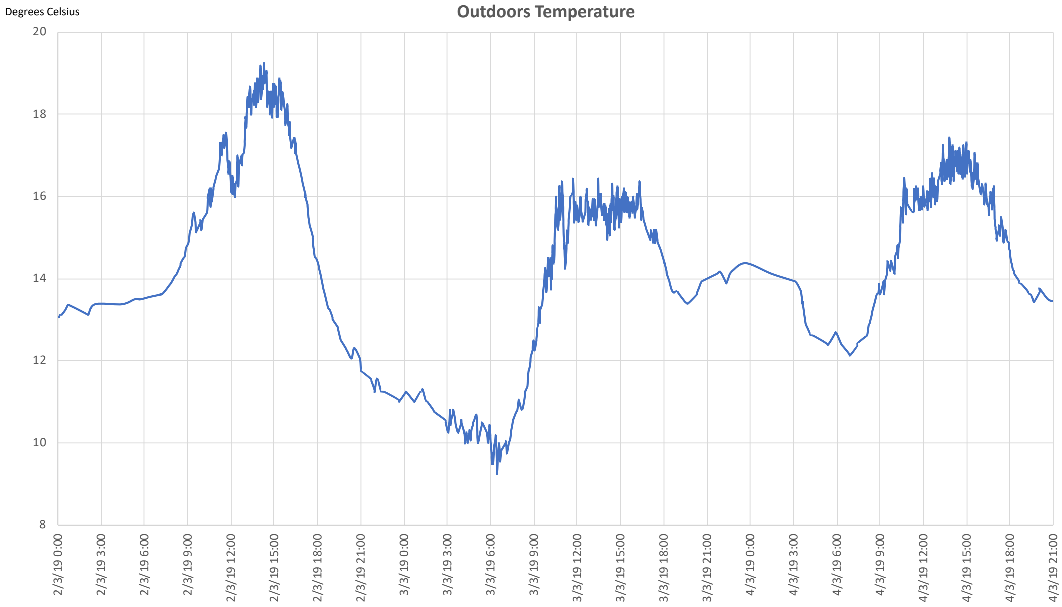

Figure 5.4: Outdoors Temperature levels recorded during the winter baseline study period

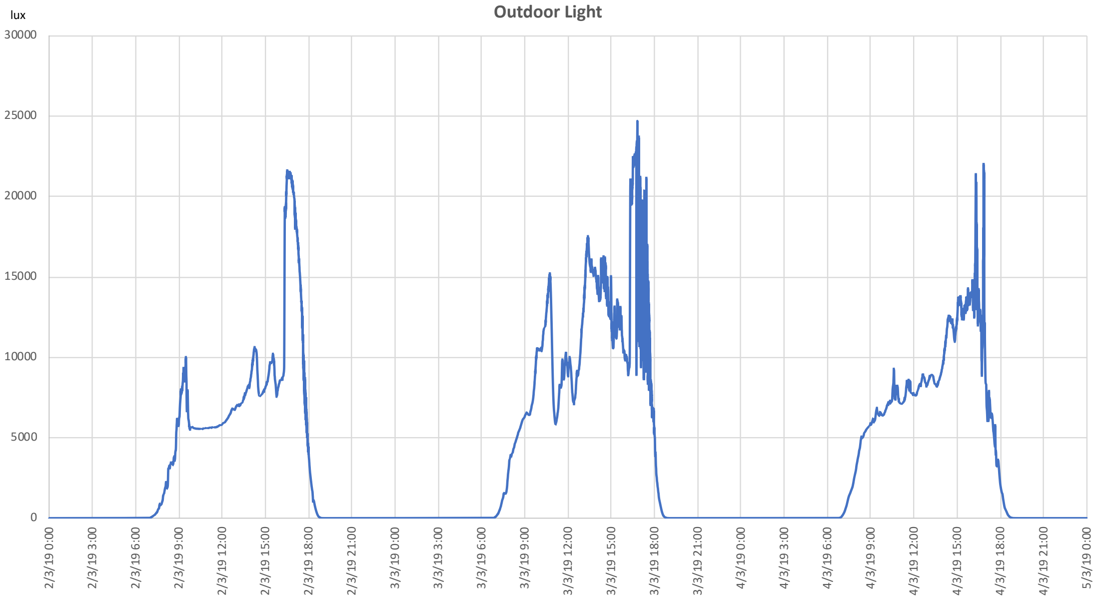

Figure 5.5: Outdoor Light levels recorded during the winter baseline study period

Although the laboratory only has an area of 44.44 square meters, differences between the workstations temperature variations were observed. The workstations located closer to the windows registered lower temperatures during the morning period than the workstations situated farther from the windows. As an example, we present the workstations one and eight temperature variation in figure 5.6. There are also differences regarding the workstations light levels, as workstations closer to the windows present higher light levels. The workstations light level difference is presented in figure 5.7 and the outdoor light level variation is presented in figure 5.5.

Considering the Decree-law 243/86 presented in section 3.3.1, it is possible to observe that the target temperature ranging from eighteen and twenty-two degrees Celsius was not met during the morning periods. Regarding the light conditions, workstation one was able to surpass the minimum five hundred lux limit during some hours of the day and workstation eight did not reach once the required minimum light level. If users worked in the laboratory during the test period, they would have to use the AC unit and the available light system to maintain the appropriate temperature and light conditions.

The environmental conditions variability between different workstations should also be taken into account when implementing the Smartlab's controller. Each workstation temperature and light levels should be monitored, and adequate conditions in a particular workstation should not come at the expense of another workstation condition.

The Smartlab controller must take into consideration the winter baseline environmental conditions, without overfitting to the observed indoor and outdoor conditions. The BAS controller should be prepared to operate in all four weather seasons. To achieve this goal, the controller must be prepared to sacrifice its energy efficiency intents to ensure the occupants are provided with a suitable environment to work and the Open Aquarium requirements are satisfied.

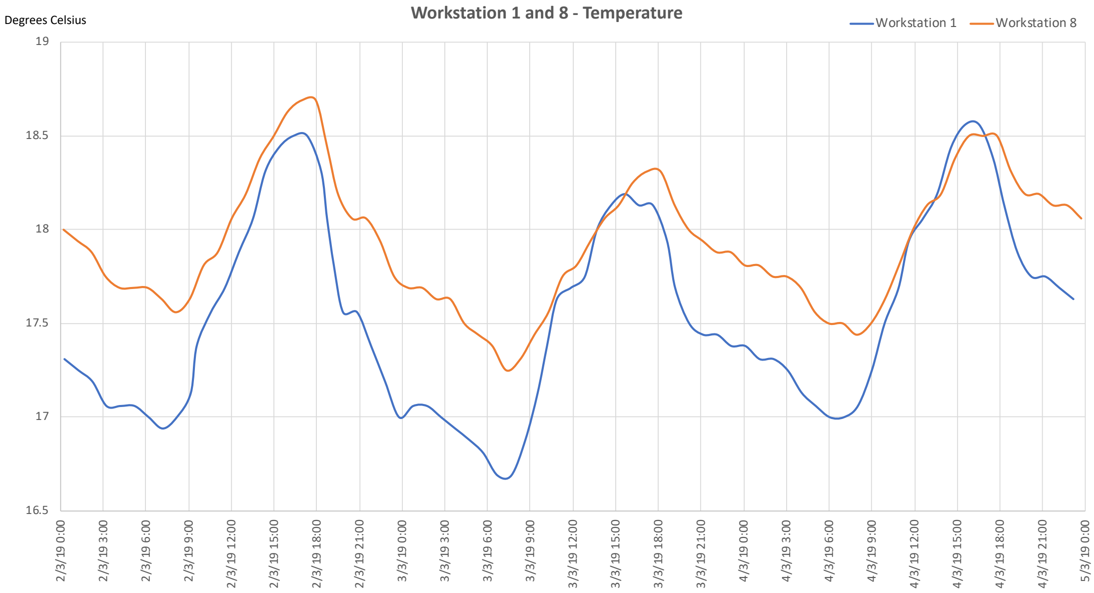

Figure 5.6: Workstations one and eight temperature variation

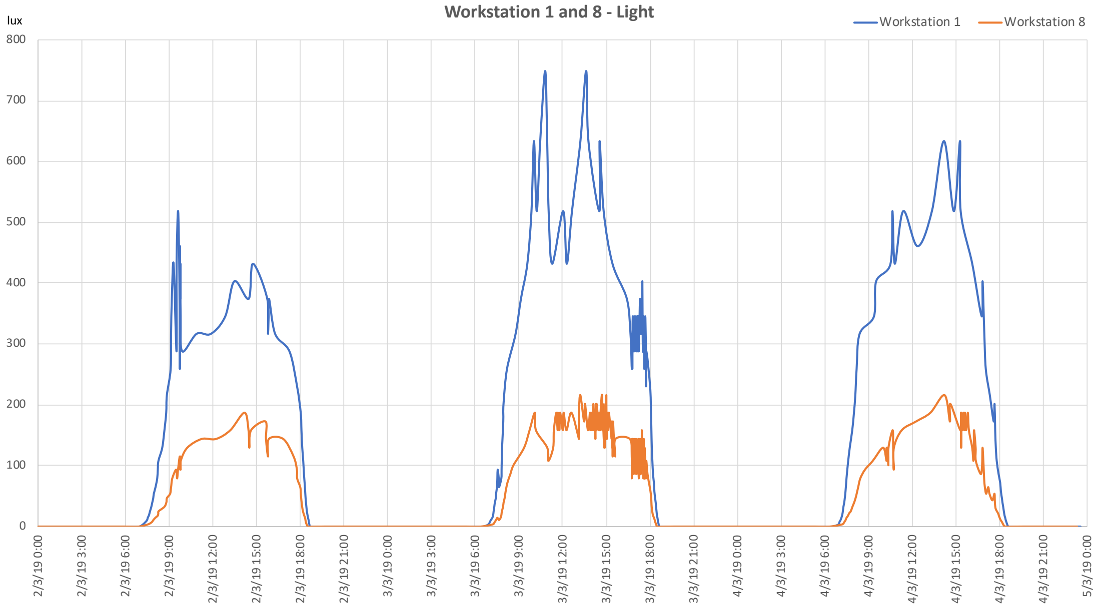

Figure 5.7: Workstations one and eight light levels variation

We also conducted a baseline study during the summer to access the weather variability to which the laboratory is exposed. The aquarium's water cooler cools the water by blowing air to the water surface, and it is only effective when a small difference between the planned water temperature and the actual water temperature exists. The decision was made to leave the air conditioner unit turned on with a temperature setpoint of 21°and configured in auto mode, to ensure that the aquarium water's temperature would not put the aquarium's fishes comfort in danger. The test was conducted in the summer and during the three day the sky was clear of clouds. It is shown in figures 5.14 and 5.15 that the AC unit is not able to maintain the temperature levels steady at 21°and that workstation temperatures reached higher values than the legally defined maximum target of 22°.

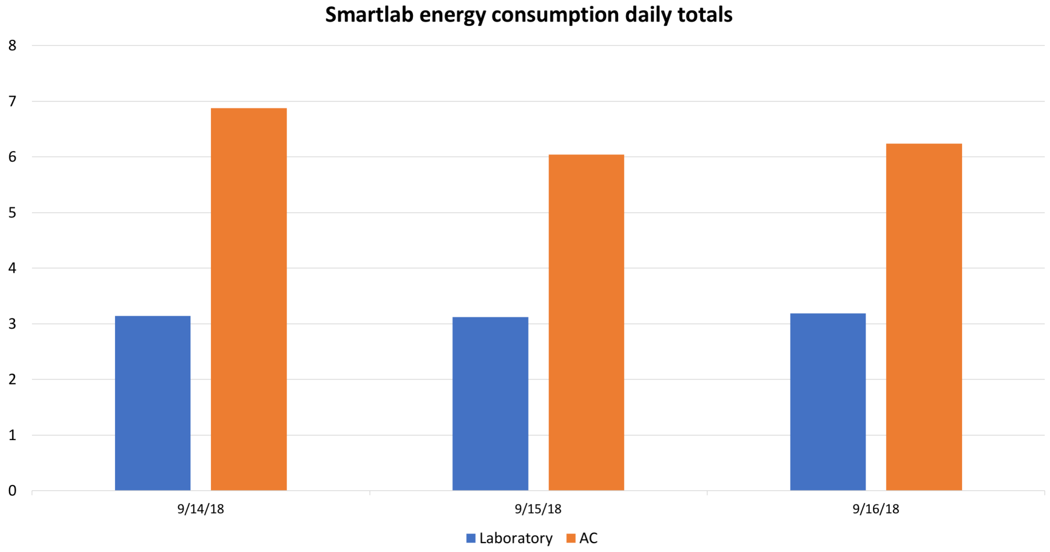

Figure 5.8: Smartlab summer baseline daily energy consumption

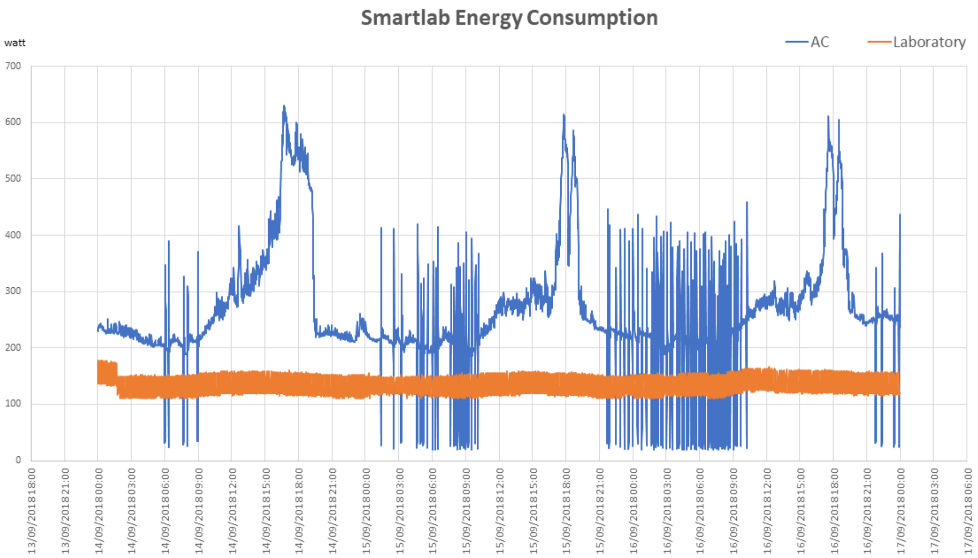

Figure 5.9: Smartlab summer baseline power consumption

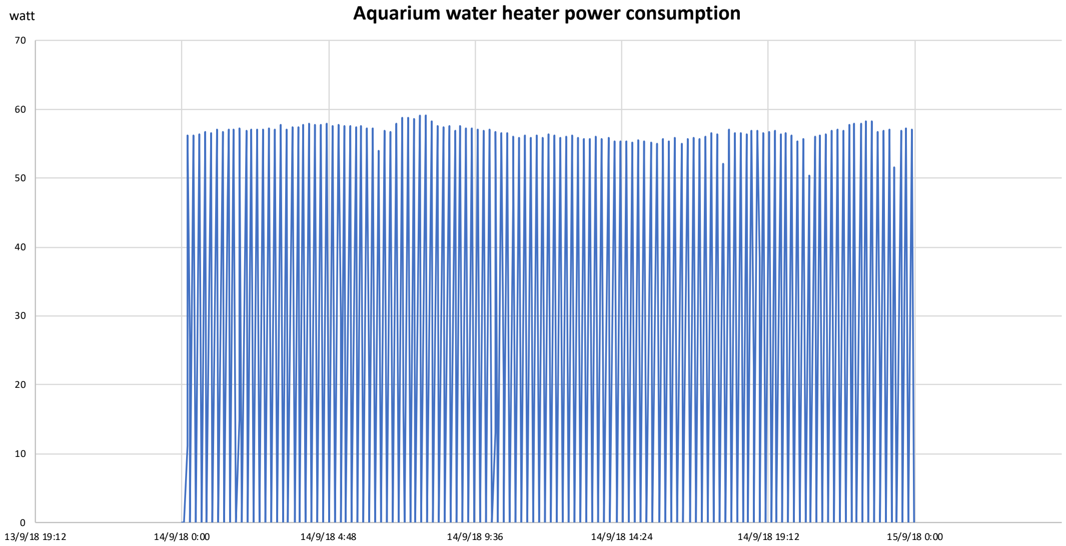

Figure 5.10: Aquarium's water heater power consumption during one day

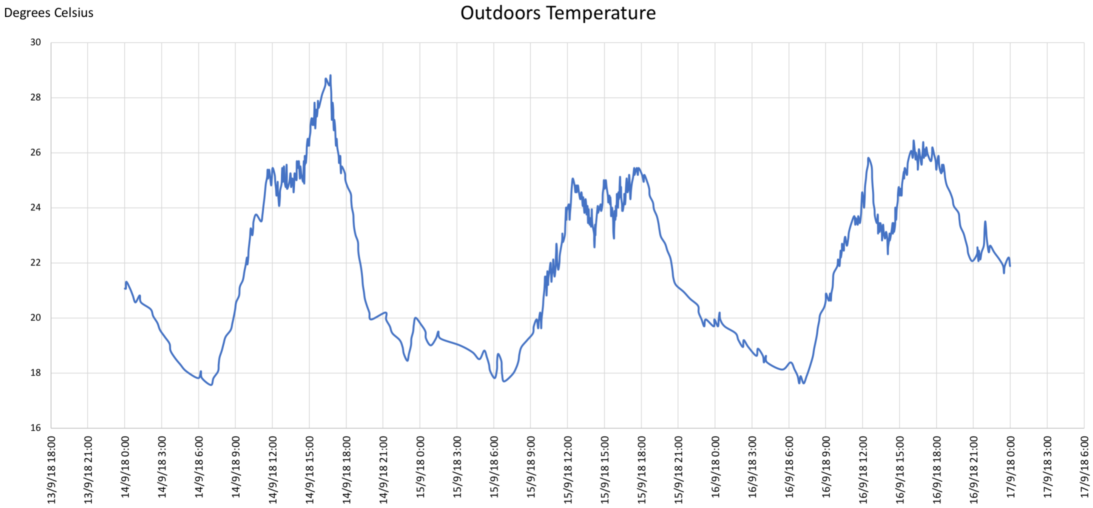

Figure 5.11: Outdoors Temperature levels recorded during the summer baseline study period

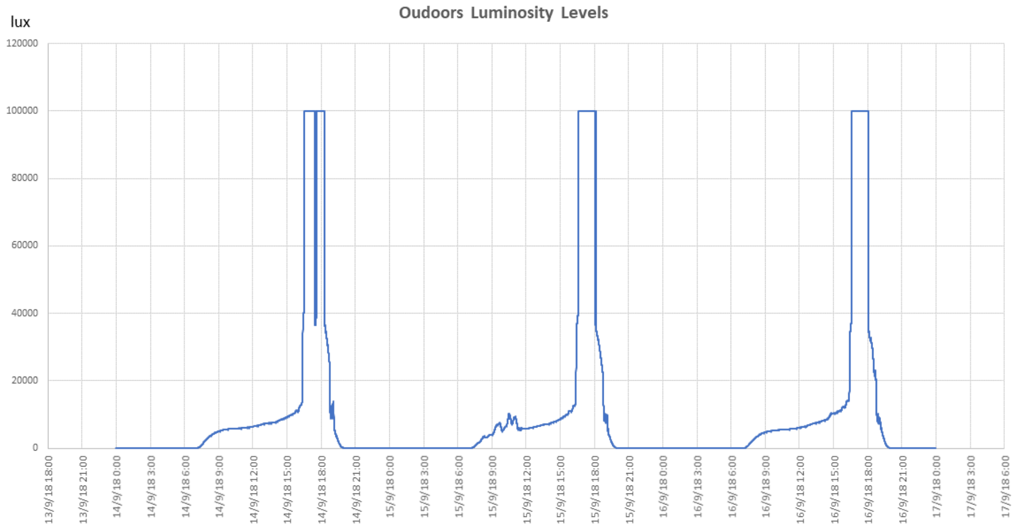

Figure 5.12: Outdoors Luminosity levels recorded during the summer baseline study period

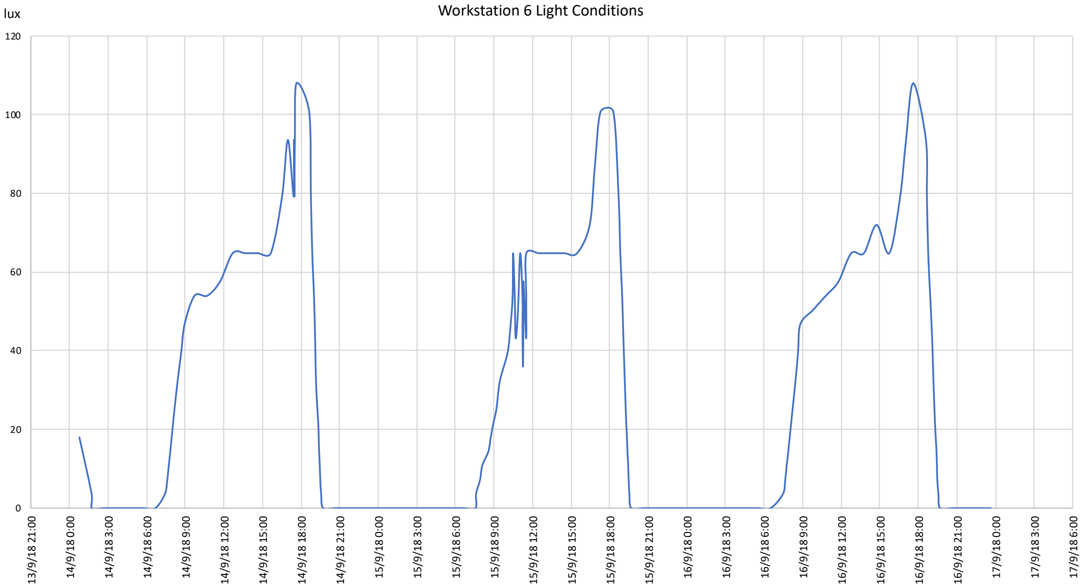

Figure 5.13: Workstation six luminosity levels recorded during the baseline study period

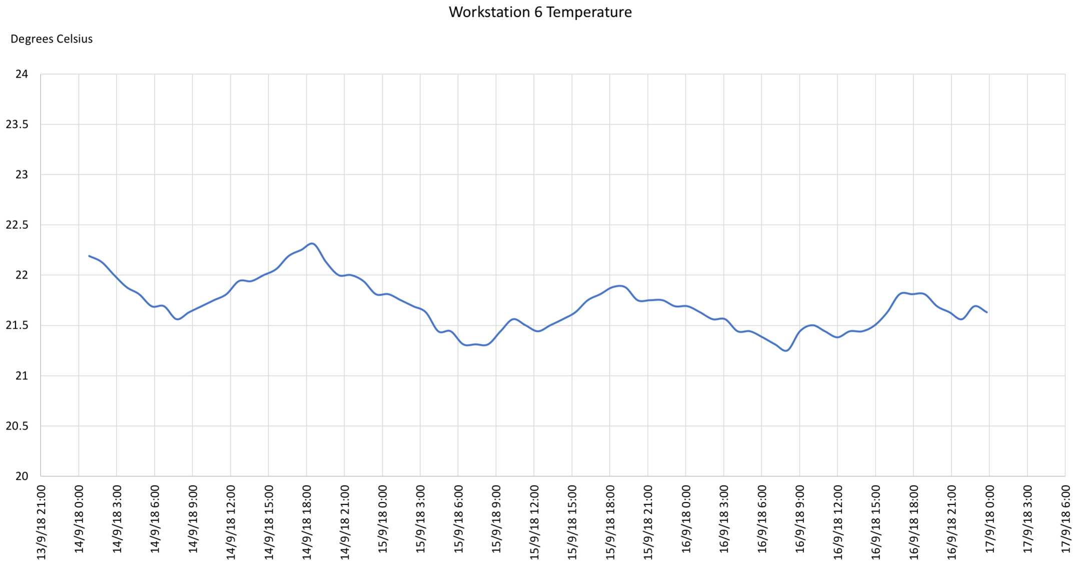

Figure 5.14: Workstation six temperature levels recorded during the baseline study period

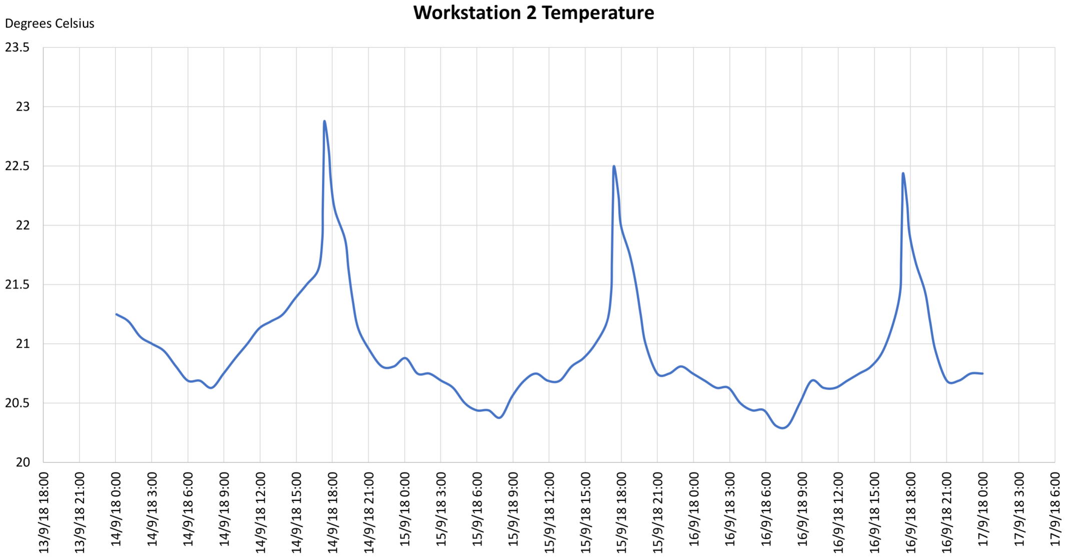

Figure 5.15: Workstation two temperature levels recorded during the baseline study period. The AC equipment is not capable to maintain the workstation temperature within the legal temperature targets

5.4 First Empirical study

In the first empirical study, humans are entirely in control of the Smartlab actuators. It is their responsibility to manage the temperature and light conditions that are available to them. The Smartlab's controller is not managing the available laboratory actuators, and it is only collecting sensor data. The data collected helps us to pinpoint actions that lead to energy waste and possible changes to users behaviours that promote energy savings. With the data collected, we can evaluate if the users are working in the conditions presented in section 3.3. If the minimum requirements are not met, there is the possibility of negative effects on the users' health and productivity.

5.4.1 Collected Data

During the three days of testing, the sky was partially clouded, the outdoors luminosity pattern was similar throughout the three days, and the temperature varied from a minimum value of 7,25°and a maximum value of 18,81°. The outdoors temperature and luminosity variation during the test period are presented in figures 5.16 and 5.17 respectively.

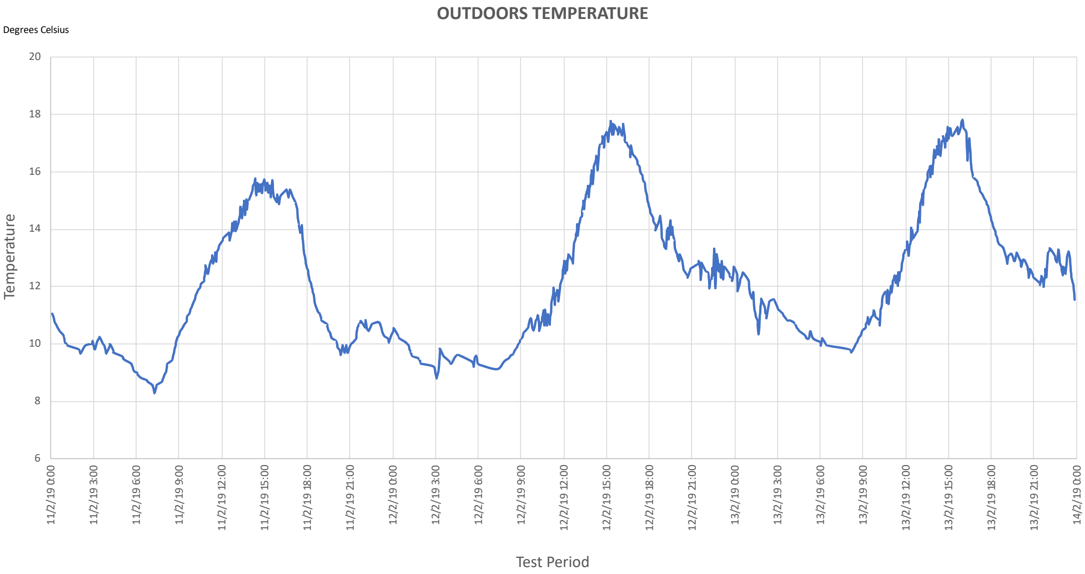

Figure 5.16: Outdoors temperature variation during the three days test

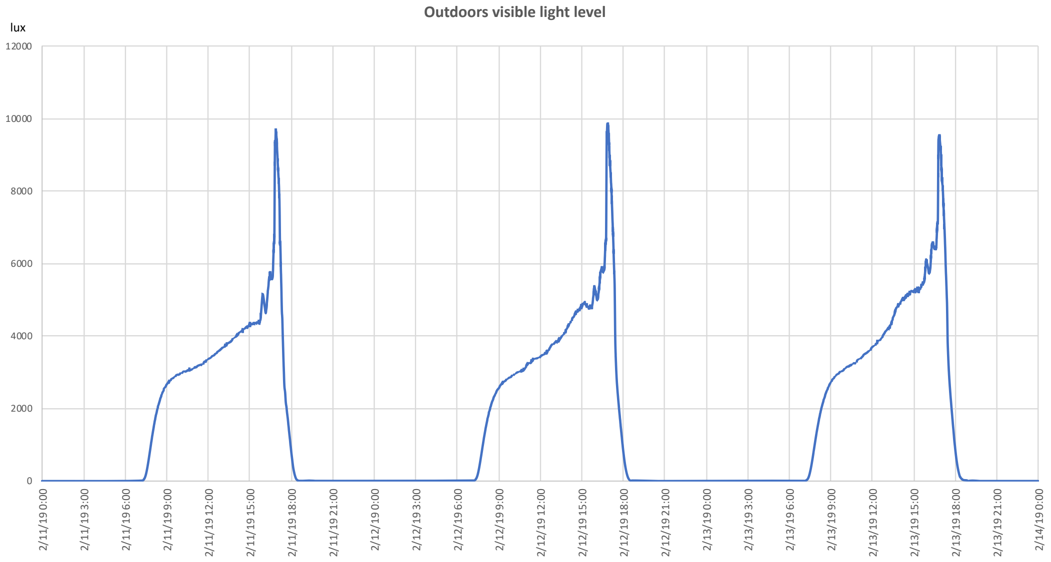

Figure 5.17: Outdoors visible light variation during the test

Throughout the time of the test, the Smartlab's infrastructure consumed a total of 54.39kWh. The energy expenditure variation between the three days of testing and the breakdown of the energy totals between the AC unit and the rest of the Smartlab's devices is presented in figure 5.18.

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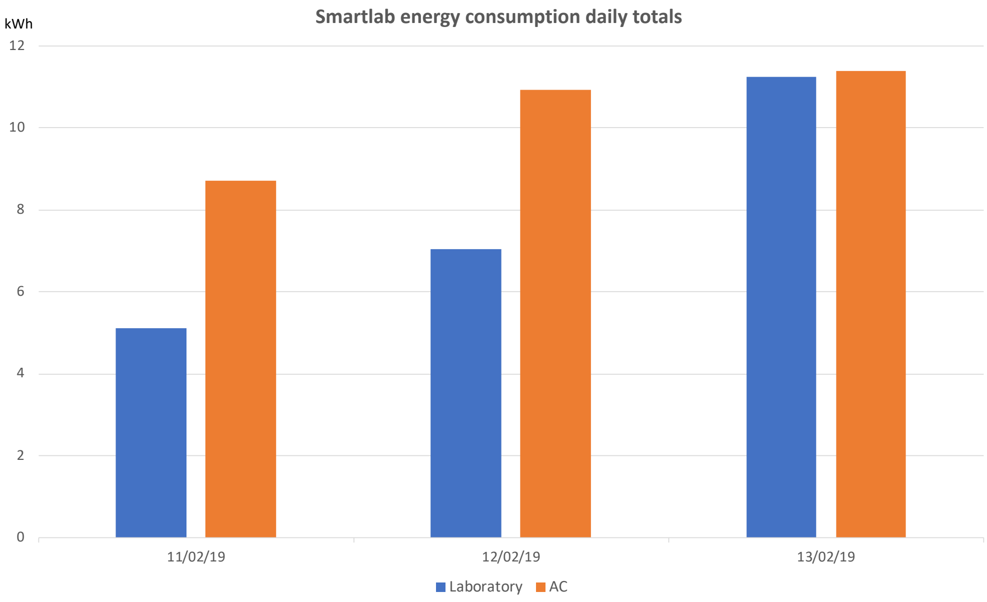

Figure 5.18: First empirical study energy consumption

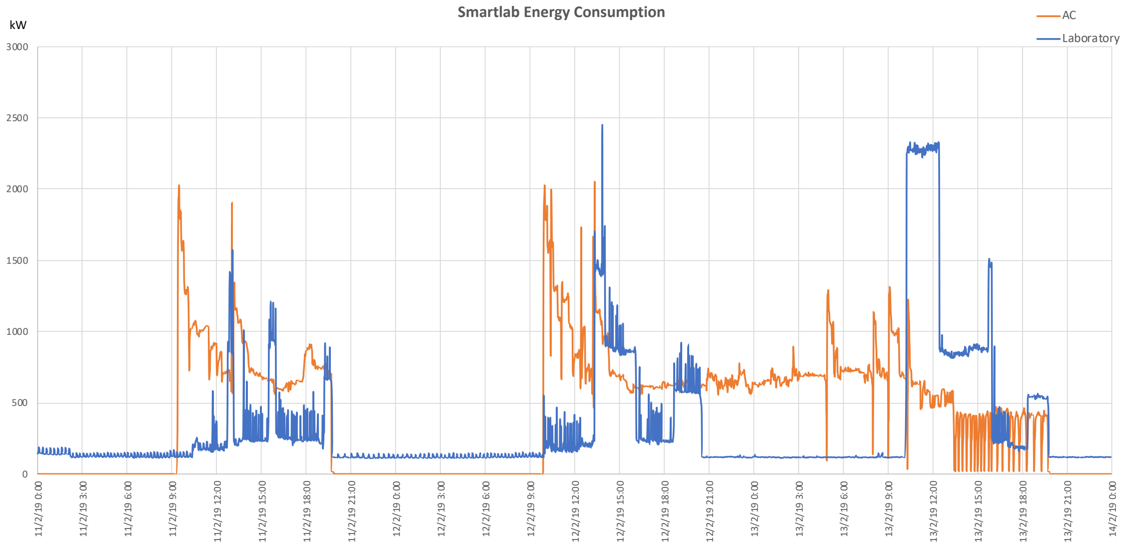

Figure 5.19: Power consumption variation during the test

We start by analysing the temperature conditions that the users had to endure during the test. Small variations in the workstations temperature sensors were detected. The workstations closer to the windows registered the highest temperatures and workstation eight presented the lowest temperatures. The highest difference between workstations temperature at a given time was 1.12 degrees Celsius, and all workstations presented a similar temperature variation during the days. In figure 5.20 is presented the temperature variation of the workstation that averaged the lowest temperature, workstation two and the temperature variation of the workstation that averaged the highest temperature, workstation eight.

On the first and second days, users were working in temperatures below the eighteen degrees Celsius minimum limit until the end of the morning period on the first day and on the second day only at 13h47m all users were working at temperatures above the minimum legally imposed target. On the third day, this situation was not a problem because workstation four's user forgot to turn off the AC unit when finishing his working day. However, this caused a significant energy waste as the next day's first occupant arrived only at 10h13m. This situation helped us identify a key feature for the Smartlab's controller that will be tested in the next experiments: when the last user leaves the room for an extended period, the system should turn off the AC unit, the light bulbs and the user associated power outlets. By turning off the power outlets, we intend to save energy when users leave the office and forget to turn off additional equipment that they bring to the office like, displays or personal heaters.

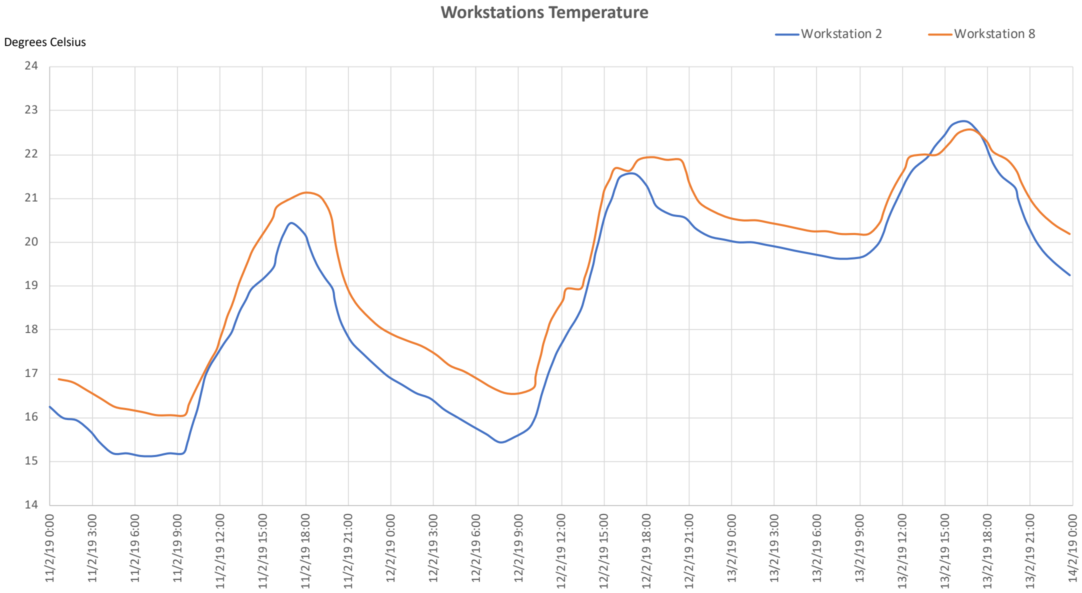

Figure 5.20: Workstation 2 and 8 temperature variation during the test days

When entering the office, workstation nine and ten users felt that the room's temperature was lower than their prefered temperature. In figure 5.21 it is possible to see that the users decided to use their personal heaters located at their workstations. These heaters are energetically inefficient, and their effect is mostly felt by the users in the path of the hot air stream. As the distance from the heater increases the effect on the workstations temperature is reduced. The workstations temperature variation collected in the baseline study, presented in figure 5.7 combined with the data presented in figure 5.20 reveals that there was not an immediate effect on the room's temperature. However, after some hours running they contribute to an increase in the room temperature, and this was more noticeable on the third day when the room temperature surpassed the twenty-two degrees Celsius legal limit. As Zeiler, Houten and Vissers [52] work indicates, humans are shown to generate energy waste when they act to change uncomfortable conditions. It was noticeable on the second and third days that workstations nine and ten users decided to start their heaters at the maximum power setting available and they turn off one their devices resistors when they felt that the temperature was appropriate.

The use of personal heaters also raises the problem that a single user is able to change the room environmental conditions that can make another user feel uncomfortable. During the third-day workstation ten's user turned on his heater even though his workstation temperature had already surpassed the twenty degrees Celsius mark. At 13h20m workstation one's user unaware that there another heat source besides the AC unit, lowered the AC set temperature to a temperature lower than the room's temperature. As the equipment was set in heat mode, this action also resulted in energy waste as it is shown in figure 5.19 when the device started to present an irregular power consumption behaviour at 13h20m.

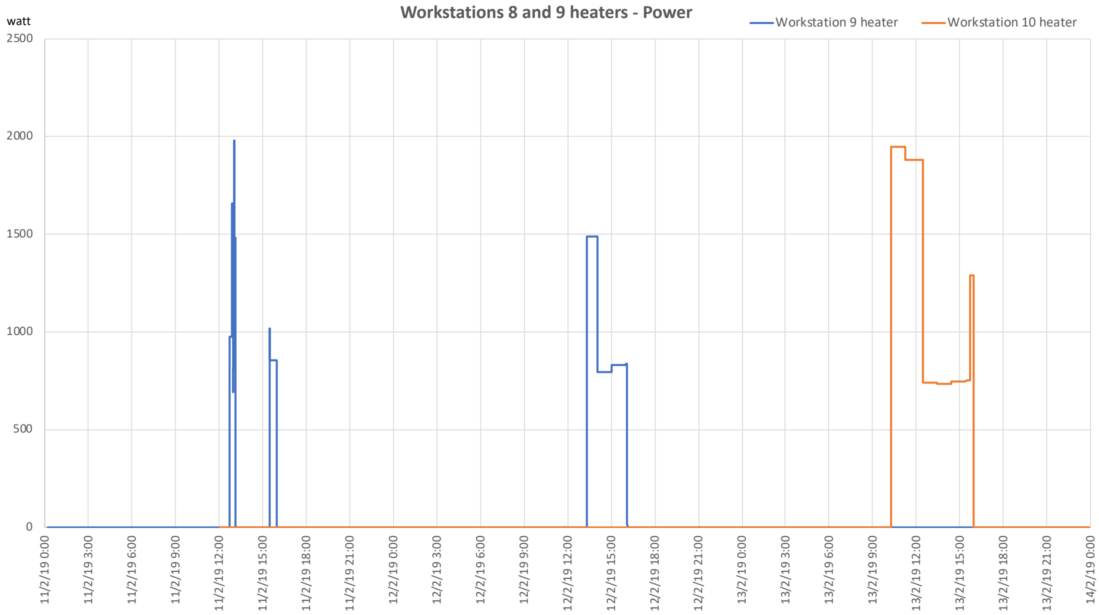

Figure 5.21: Workstations 9 and 10 heaters power outlets

The Smartlab controller should accommodate different user temperature, and light level preferences while complying with the legally imposed target conditions. Our objective is to eliminate the use of personal heaters. To achieve this goal, users have to feel comfortable when they arrive at the office.

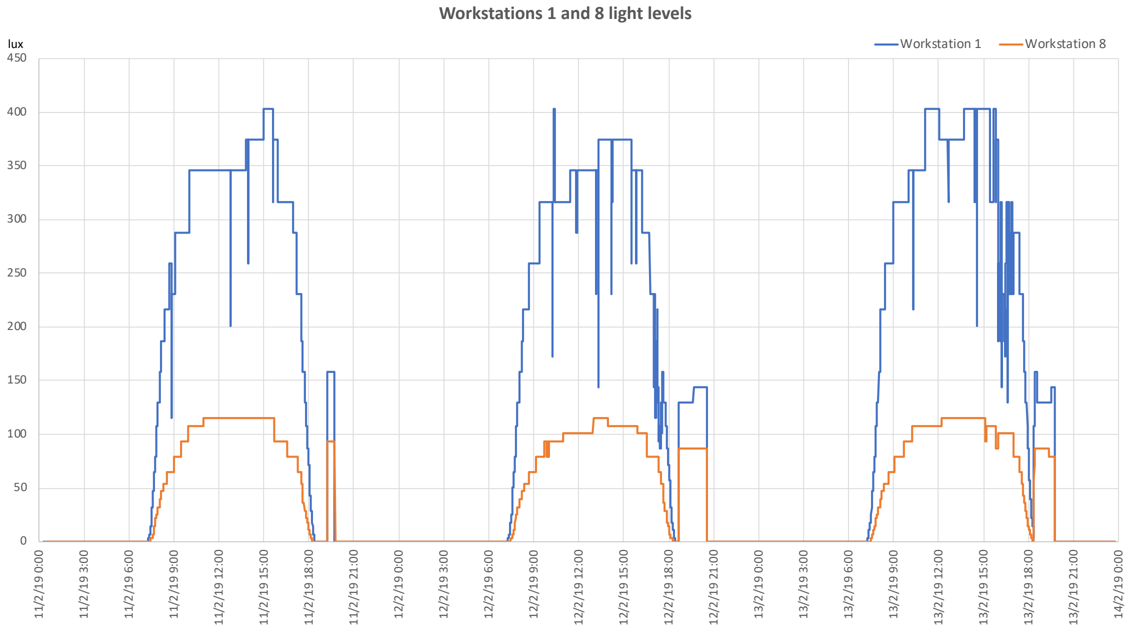

Figure 5.22: Workstations one and eight light levels

We now change the focus to the light levels that the occupants had to experience throughout the test. During the first empirical study, the occupants always worked under light levels below the legally required target of five hundred lux. In figure 5.22 is presented the light level variation of the workstation that averaged the lowest light level, workstation eight and the temperature variation of the workstation that averaged the highest light level, workstation one. In the long run, working for extended periods of time under inadequate light conditions can have a negative impact on the occupants' health as shown in section 3.3.2. At the end of the study's first-day, the power socket data presented in figure 5.23 shows that workstations two and four users were working. Their workstation light sensor data presented in figure 5.24 reveals that they were working in low light conditions, having as the sole source of light their laptop display.

It was also observed that the users used only the halogen lights installed at the ceiling. There are potential energy savings by changing the primary artificial light source to the Lifx LED lights as each set of halogen lights consumes 340 watts when activated, comparing to the LED power consumption of 11,42 watt when the brightness is set to maximum level available.

To address the low light levels that users reported during the first empirical study, the Smartlab's controller that was implemented for the next two empirical studies seeks to maintain a minimum light level of five hundred lux at each workstation when the occupants are working.

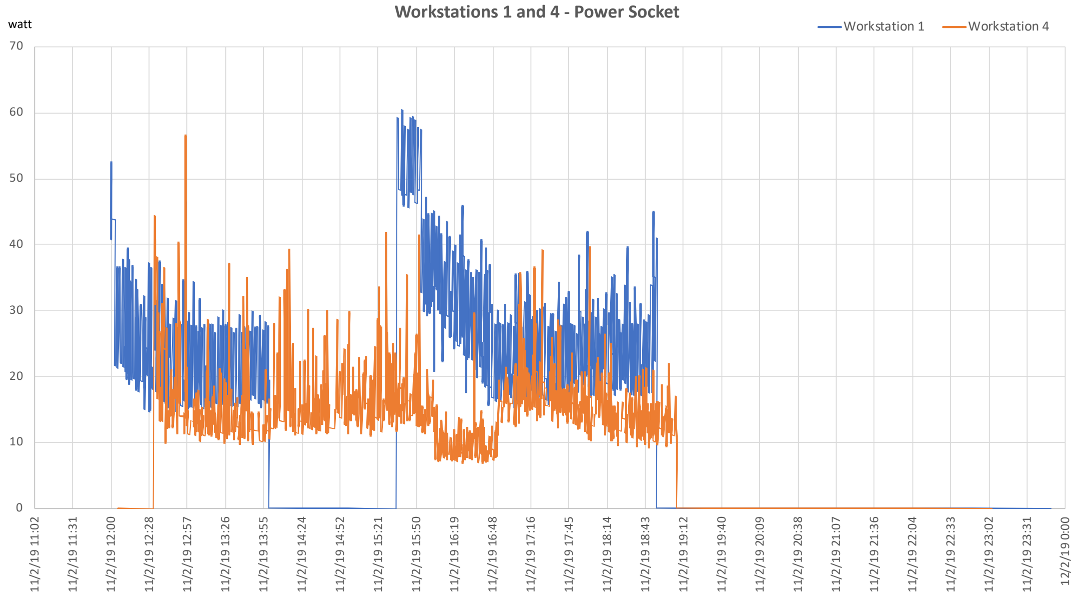

Figure 5.23: Workstations one and four power socket activity

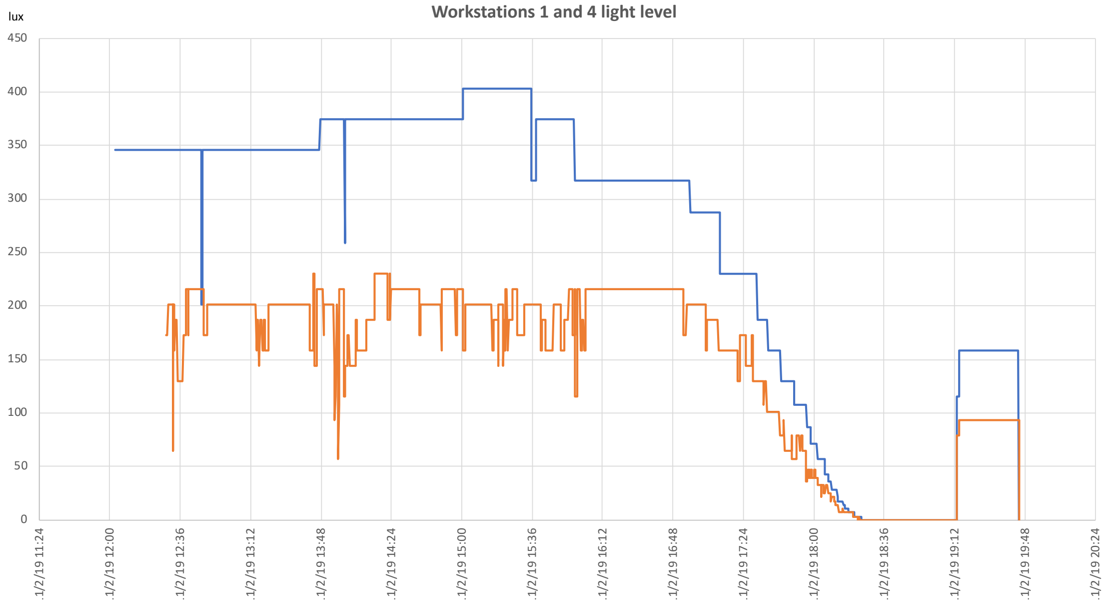

Figure 5.24: Workstations one and four light levels during the test first day. Users were working in low light conditions

5.4.2 User survey

Four users replied to the survey[1]. 75% are women, and the age average is 25 years, and 100% reported as having myopia. Considering the current Smartlab's occupants, it is essential that in the future adequate light level is provided because insufficient light plays a role in myopia development and progress, as shown in section 3.3.2. Users provided the following feedback regarding the environmental conditions during the three days:

- 50% found the office's temperature adequate, and the other 50% found the temperature between adequate and hot.
- When arriving at the office 75% found the office's temperature between cold and adequate, while 25% classified the temperature between adequate and hot.
- 75% found the office's light as adequate and 25% assessed the light level between insufficient and adequate.
- Three out of four users indicated that they tried to maintain their optimal temperature and light working conditions.

The users' feedback[2] regarding the temperature and light levels presented in the previous section raise questions whether occupants can provide reliable evaluations regarding the working light levels.

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[1] https://joao980917.typeform.com/to/OXjITh (accessed 25-03-2019)

[2] https://joao980917.typeform.com/report/OXjITh/RyDuKASq6MW6OgjY (accessed 25-03-2019)

On the open question, three out of four users submitted suggestions with the objective to improve the laboratory conditions. Two users complained about the windows' insulation. These were the workstations one and two users. Workstation nine's user indicated that he would like higher temperatures during the first and second days. This feedback is corroborated by the user use of his heater on the mentioned days.

5.5 Second Empirical study

5.5.1 BAS controller

On the second empirical study, the BAS's controller is working autonomously to achieve energy savings while maintaining appropriate environmental conditions available to the room occupants.

To implement the BAS controller we started by identifying all the necessary BAS participating entities that the controller needs access to fulfil its goals. To persist the entities our choice was to define a MySQL database schema. This schema was then deployed in the MySQL server that the WSO2 IoT solution is also using to persist its data. The database instance is also used by the REST API mentioned in section 4.7.1 to persist the data exchanged with the Android mobile application made available to the Smartlab's occupants. The database schema Enhanced Entity-Relationship (EER) diagram is presented in figure 5.25. The controller application is a Java 8 EE application and the Hibernate Object-Relational Mapping (ORM) framework for data persistence via Java Database Connectivity (JDBC). The data exchanged by both the REST API Service, the controller application and the database instance is Transport Layer Security (TLS) protected. For this purpose, the MySQL server is configured to use SSL certificates to ensure the database connections privacy. The Payara [3] server that hosts the controller's Java API for RESTful Web Services (JAX-RS) API is configured to only to accept client connections that are TLS protected.

The server configuration, the Payara server deployment and the controller's applications were executed during the work that we present and the BAS[4] and the REST API[5] class diagrams are available at this work's Github repository.

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[3] https://https://www.payara.fish/ (accessed 25-03-2019)

[4] https://github.com/jmpcambeiro/fctthesis/blob/master/smartlabController_class_diagram.png (accessed 25-03-2019)

[5] https://github.com/jmpcambeiro/fctthesis/blob/master/smartlabrestapi_class_diagram.png (accessed 25-03-2019)

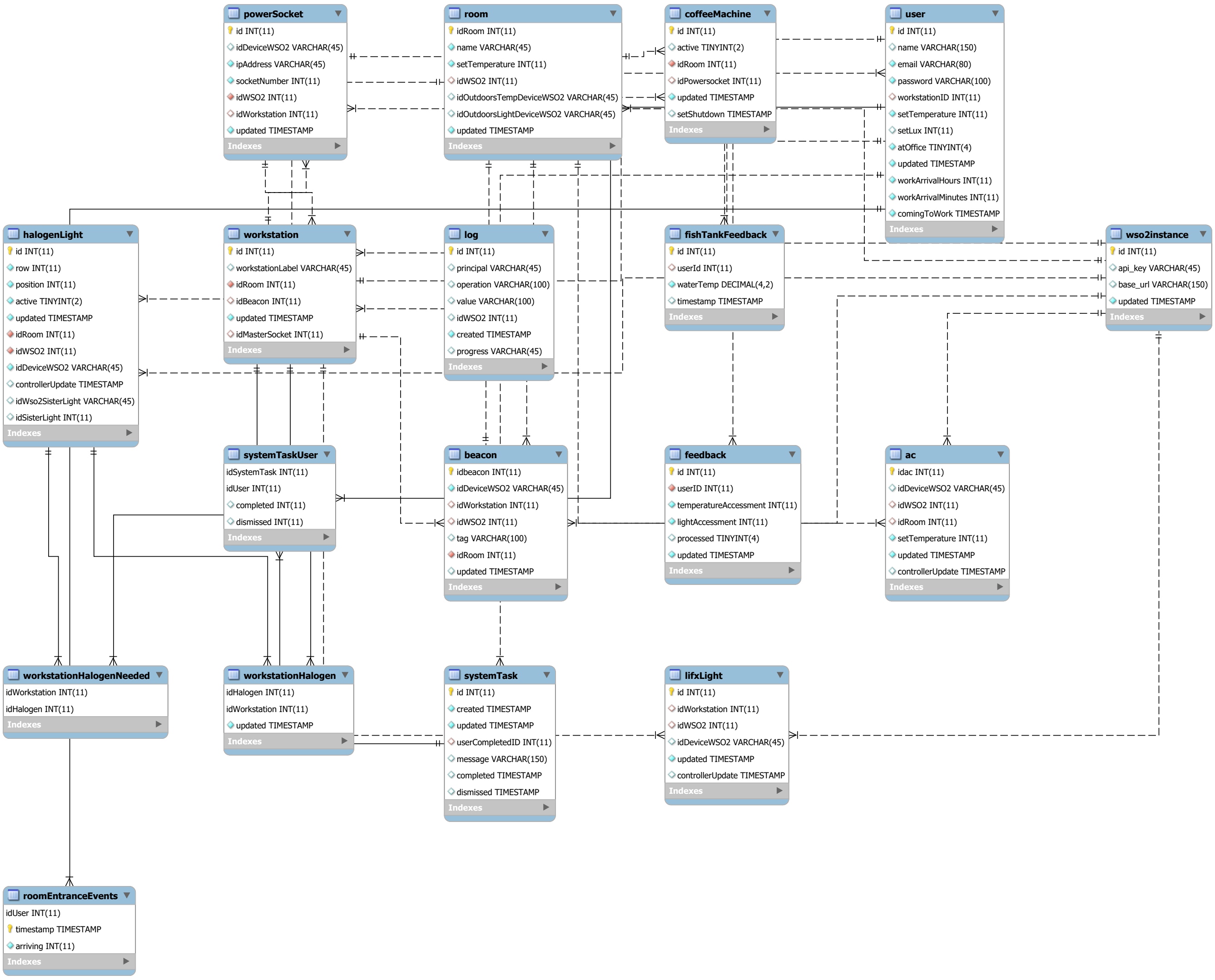

Figure 5.25: Controller database schema EER diagram

To achieve its goals the system has to keep track of the users that are present at the laboratory. For this purpose, the system relies on the indoor location system and the mobile application presented in sections 4.3.2 and 4.7.1 respectively. Users were asked to plug their laptops chargers to a predefined power socket. We consider this power socket as the user's associated workstation master socket. The controller checks the master socket power consumption to verify if the socket is needed. This feature was necessary because users sometimes leave the office for brief periods and they leave tasks being executed in their laptops or the computer's battery needs charging. If the controller cuts the power to the outlets every time that a user moves out of the room, it was possible that the users could lose their work. However, rest of the user's workstation associated power outlets are enabled or disabled if the user enters or leaves the room — this way energy is saved by turning off displays or other non-essential equipment when occupants leave the office.

In the first study, one of the identified controller features was that the system has to accommodate different occupants environmental preferences to prevent actions from users that result in energy waste. To support this feature, users can provide their light and temperatures preferences by using the mobile application preferences interface presented in figure 4.23. The users' selected preferences must comply with the legally defined temperature and light targets.

Users were also required to provide an estimated time of arrival at the office. This information provides the controller with the opportunity to set an office temperature closer to the users' selected temperature right when they arrive to work.

During the baseline studies performed during the winter and the summer, the AC unit showed in certain weather conditions that it could not keep the room temperature at the AC set temperature. These situations occurred when there was a difference higher than six degrees between the outdoor temperature and the AC set temperature. The equipment also presented an increased energy consumption with no clear benefits for the users as the difference increases. For the second and third empirical studies, we decided that the controller cannot set the temperature to a value that presents a difference from the outdoor temperature higher than six degrees Celsius.

As mentioned before the Smartlab environment is a computer science laboratory. The occupants are most of the time performing tasks that require concentration. As such the BAS controller has to take into account the expected effect that changing the available actuators might have on the users' attention. To address this issue, we decided that changes to the Lifx LED lights' brightness take twenty seconds to complete and the activations/deactivations of the halogen lights trigger a backoff period where the controller cannot change the halogen lights state.

There is also a backoff period applied to restrict changes to the AC set temperature. Changes in the AC set temperature need a certain period to reflect on the laboratory's temperature. The period value is dependent on both the outdoor weather and the CPS indoor plant state. In order to evaluate the effect of a change in the AC set temperature, a one hour backoff period was introduced.

The controller analyses every minute the temperature and light conditions and changes the BAS's actuators state as it is necessary to provide an environment that promotes the user's productivity and health. The analysis of the collected data during the baseline and the first empirical studies combined with the user feedback that was received at the end of the previous study contributed to the implementation of the following set of control rules:

- Temperature
    - If there are no users at the office - If there are not users expected to arrive at the office in the next sixty minutes, the AC should be turned off otherwise the AC set temperature is the average of preferred user temperatures that are arriving soon.

  - If there are users at the office - If a user is working in temperatures that do not comply with the legally defined targets, the AC temperature is increased or decreased considering if the workstation temperature is too cold or too hot. If all the workstations temperatures that have users working lie between the eighteen and twenty degrees Celsius, then the AC set temperature is equal to the average of the occupants preferred temperature.

- Light
  - A user arrives at the office, and his workstation's light level is less than the user's set light level - If the user associated workstation's light level is less than two hundred and fifty lux, the workstation's LED light's brightness is set to the maximum value possible. Otherwise, the light's brightness is set to 15% of the lights maximum brightness level.
  - A user exits the room - The system turns off the user workstation 's Lifx light. If a halogen light that was being used is not needed by any other workstation the halogen light is switched off.
  - A user is working at his workstation, and his workstation's light level is less than the user's set light level and LED light's brightness is less than 100 - the light's brightness level is raised 15%. The updated brightness cannot surpass 100.
  - A user is working at his workstation, and his the workstation's light level is less than the user's set light level and the LED light's brightness is set to 100 - the system switches on the closest halogen light that is not turned on.
  - A user is working at his workstation, and his the workstation's light level value is higher than the user's preferred light level value added with thirty, and no halogen light activation is associated with the workstation - The Lifx's brightness value is decreased 5%. The updated brightness value cannot be less than zero.
  - A user is working at his workstation, and his the workstation's light level value is higher than the user's preferred light level value, there is at least one halogen light activation that is associated with the workstation, and the light level has increased thirty lux since the last halogen light activation - The system switches off one of the halogen lights that are not needed by another workstation.

- Power Sockets
  - User arriving or leaving at the office - If the user's workstation master socket is being used, the current outlet state is not changed otherwise if the user is arriving or leaving, all the workstation associated sockets are disabled or enabled respectively.

5.5.2 Collected Data

During the three days of testing, the sky was partially clouded, the outdoor luminosity pattern was similar throughout the three days, and the temperature varied from a minimum value of 8,81°and a maximum value of 20,19°. The outdoors temperature and luminosity variation during the test period are presented in figures 5.26 and 5.27 respectively.

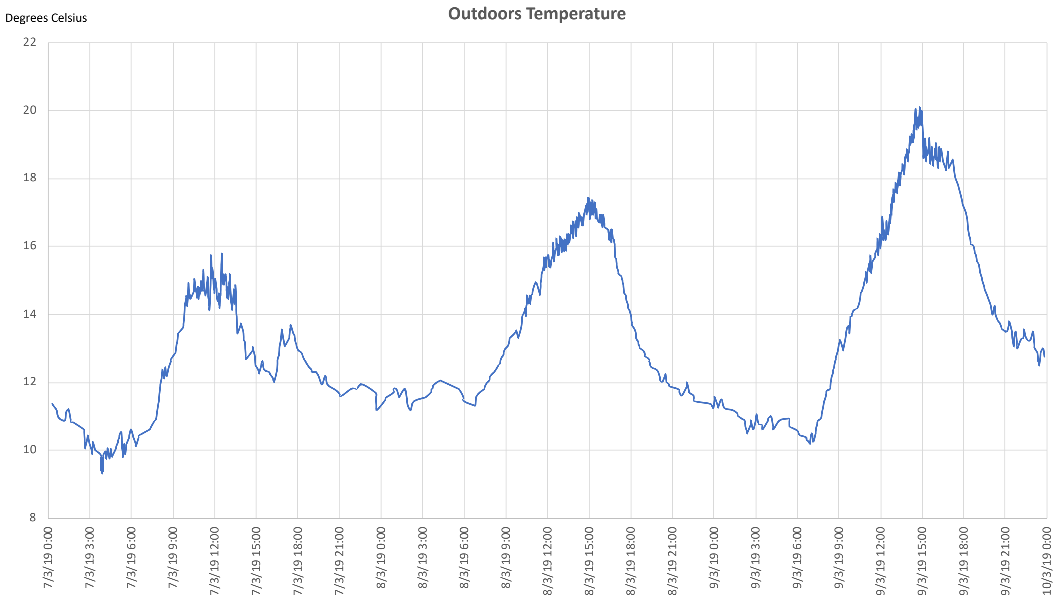

Figure 5.26: Outdoor temperature variation during the three days test

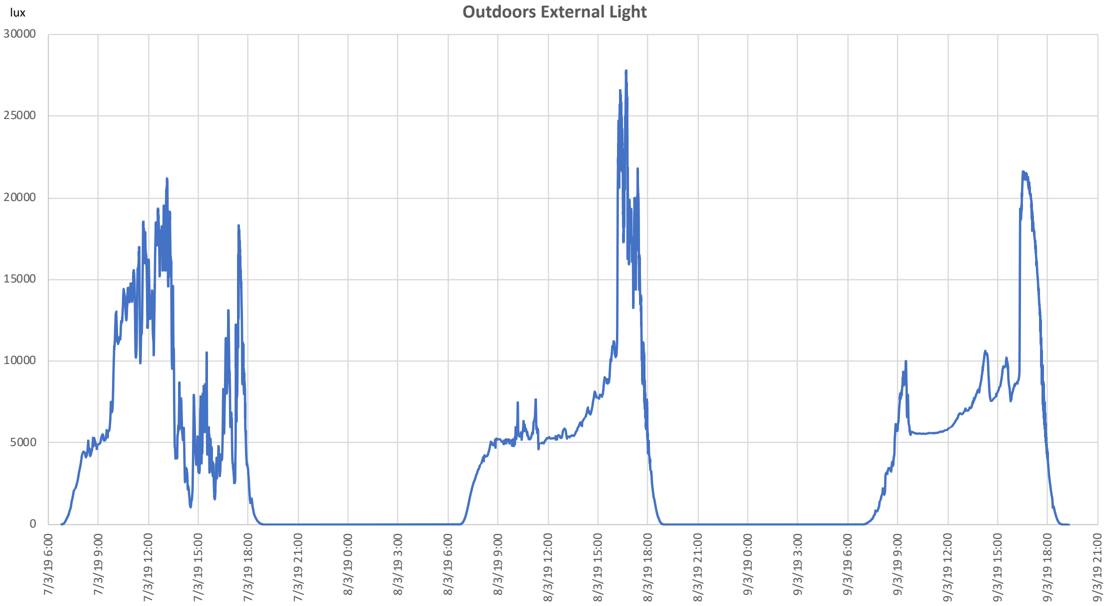

Figure 5.27: External light during the test days

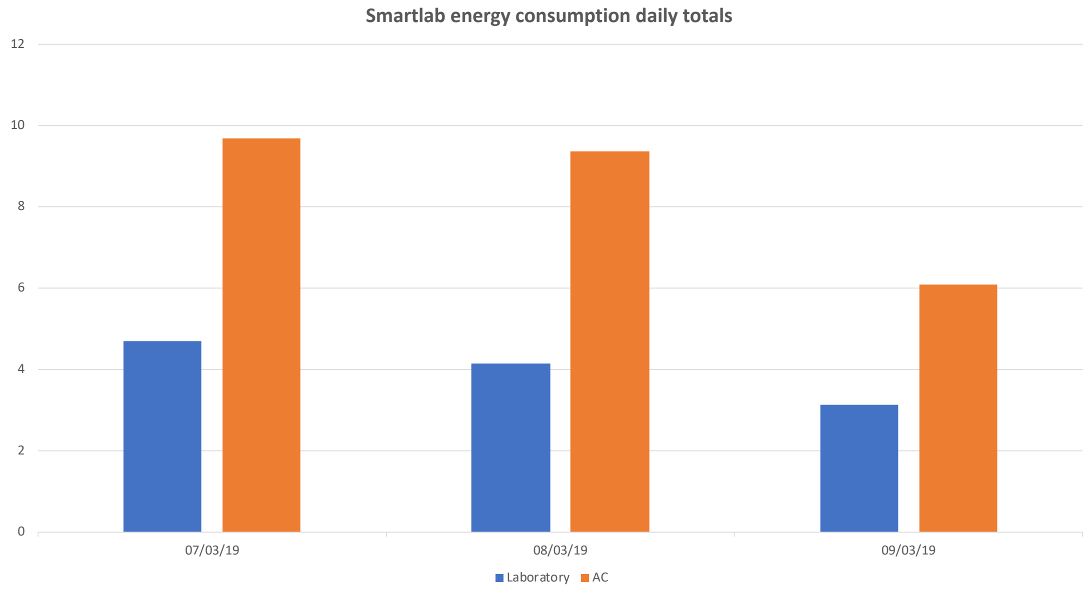

Figure 5.28: Smartlab daily energy consumption

Throughout the test, the BAS infrastructure consumed a total of 37.1kWh. The energy expenditure variation between the three days of testing and the breakdown of the energy totals between the AC unit and the rest of the BAS's devices is presented in figure 5.28.

One of the controller's goals was to achieve a more energy efficient system while providing suitable environmental conditions to the users. One of the takeaways from the first empirical study was that the most significant contributors to energy spending were the AC unit, the personal heaters and the halogen lights. The system must make more efficient use of these pieces of equipment to achieve energy savings. It was observed in the first empirical study that for one occasion the last user exiting the laboratory for the day left the AC unit running generating a significant waste of energy.

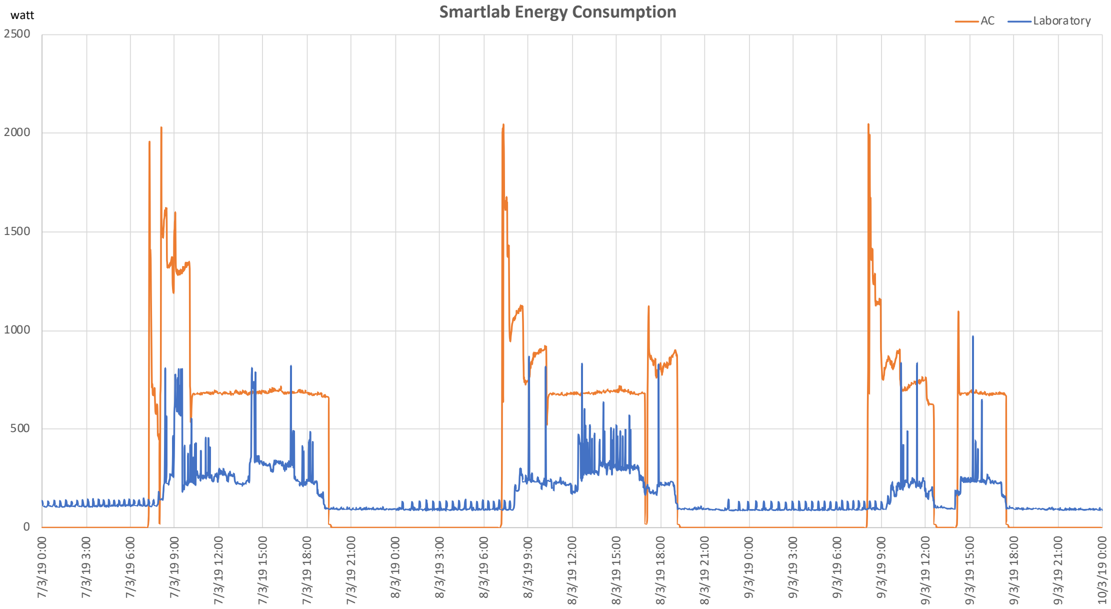

Figure 5.29: Power consumption variation during the test

During the test, the management of the AC unit's enabled state worked as expected as the BAS controller turned off the equipment when there were no users left inside the room. The AC unit power consumption and the controller activation of the device are presented in figures 5.29 and 5.30 respectively. The controller turned off the AC at the end of every day when the last occupant left the room. On the first and second days, there was at least one user at the office during the lunch period, as this is the reason why the equipment kept running. On the third day, the system turned off the AC unit during lunch as there were no users present at the laboratory. On the second day, between 17h01m and 17h03m there were no users at the laboratory, and the equipment was powered off. However, this did not result in energy savings because when the AC resumed operation, a few minutes later, it did so consuming more energy than the instant before being turned off. In a future controller version, humans could inform the system if they expect to be out of the office for an extended period and with a deeper understanding of the AC's controller, additional energy savings could be obtained. By doing this, humans would be performing the CPS feedback loop's sensor role with potentials gains to the system.

As mentioned before, this version of the controller takes as input the users expected time of arrival to the office. Before the test was started, users were asked to provide an estimated time of arrival to the office for each the test's days. Our objective was to provide the controller with the start of the working schedule for each day. At the end of each day, the system administrator updated the system information regarding the users next day time of arrival to the office.

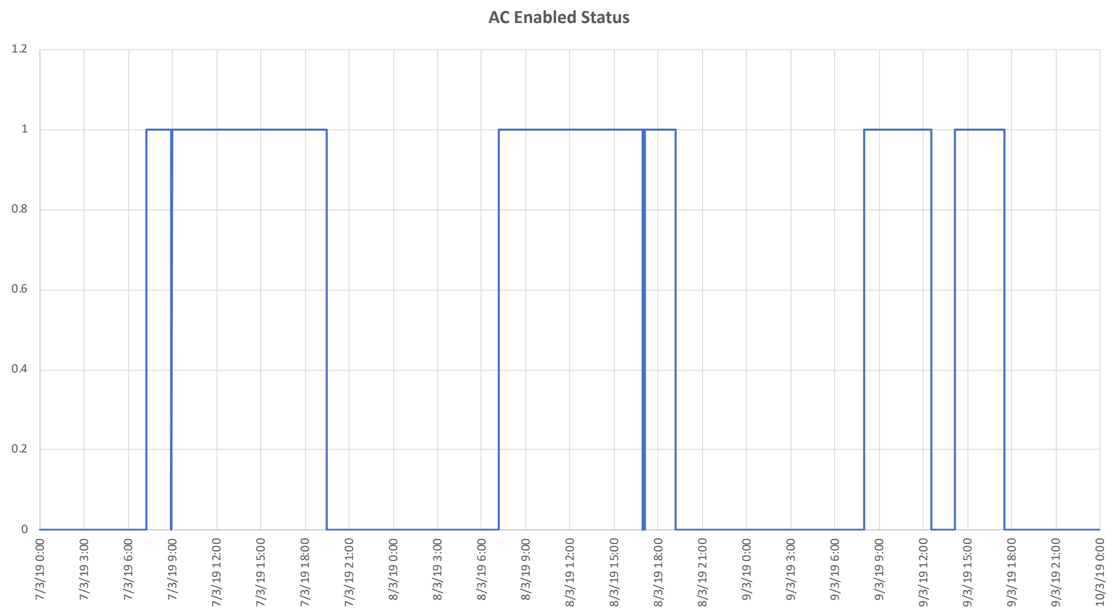

Figure 5.30: AC unit enabled status

Workstation two's user set his estimated time of arrival to 8h05m for the first two days, and the controller started heating the room one hour before, providing a warmer environment at the user's time of arrival. In figure 5.31 is presented the user's laptop energy demand. Considering data presented in the figure the user arrived at the expected time, and no significant energy was wasted. On the third-day, workstation six's user was scheduled to be the first to arrive at the laboratory. He previously indicated that he would arrive at 9h, but he arrived only at the office at 10h05m. Workstation eight's user was scheduled to arrive at 9h30m arrived at 9h37m. The controller activated the AC at 8h, and this resulted in an unnecessary thirty-seven minutes of the AC unit running. Hypothetically, if workstation eight's user did not work at the office on the third day, the waste of energy would have been the result of having the AC working and additional 1h05m. There is potentially room for improvement if the BAS allows users to change their predicted working schedule. This will provide another opportunity for humans to participate in the CPS as sensors. In this scenario, users will provide the controller with their updated working schedule data. It will also raise questions about the reliability of the data given by humans that should be evaluated.

Figure 5.31: Workstation 2 PC power consumption during the test

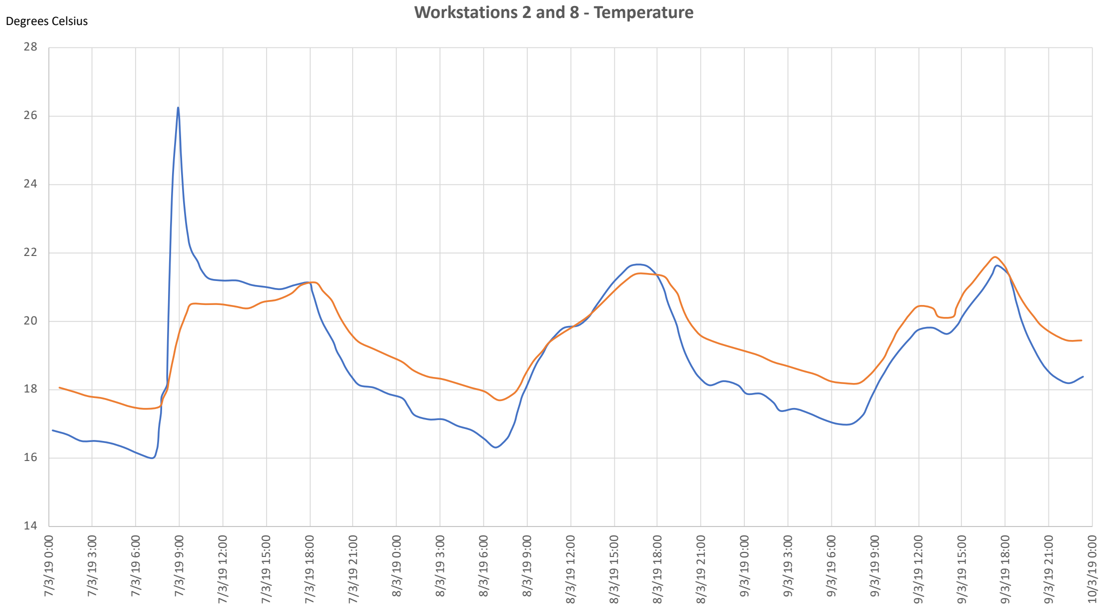

Figure 5.32: Workstations 2 and 8 temperature variation

We now change the focus to the temperature offered the occupants. All the users registered a temperature of twenty degrees Celsius as their preferred temperature. Considering that workstations two and eight users were the ones that stayed longer working at the laboratory we present in figure 5.32 their workstations' temperature variation during the test. Comparing with the data collected in the first empirical study, users spent less time working under temperatures that do not comply with legally defined eighteen to twenty-two degrees Celsius interval. On the first day, workstation two's user was the first to arrive at the office and found the office's temperature at 17.75°. Five minutes later the temperature reached eighteen degrees. On the second day, workstation two's user found the office at a temperature of 17.06°, and forty-two minutes later the temperature reached eighteen degrees. On the third day always worked under the recommended temperature conditions.

Due to an implementation error on the AC agent presented in section 4.5.3, the AC did not operate as expected on the first day's morning. The agent fault caused a sudden rise in workstation's two temperature. In figure 5.32 is shown that the workstation's temperature reported a temperature of 26,25°. The error was that the air projected by the AC unit was directed to the workstation two's location. The AC was switched off at 8h53m, the error on the agent code was fixed, and the AC unit's operation resumed at 8h59m.

From the analysis of the outdoor temperature, the AC set temperature and enabled state, is possible to conclude that the controller complied with the requirement that the difference between the outdoor temperature and the AC setpoint did not exceed the 6°. The controller enforced this requirement on all the test days' mornings. An example of the controller applying this rule is shown in figure 5.33 when the controller at 9h18m reduced the AC's set temperature to 18°due to a small outdoors temperature drop.

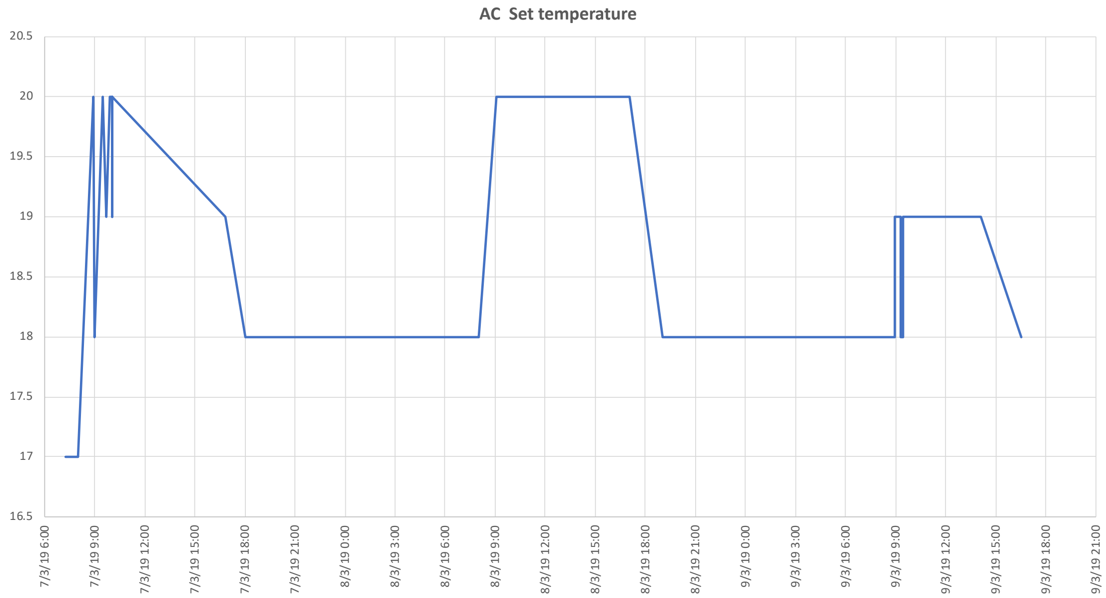

Figure 5.33: AC unit set temperature variation

Assigning a higher priority to the use of Lifx LED lights lead to additional energy savings, as the lights for most of the time were capable of maintaining the users' preferred light levels, even in low outdoor light conditions. The halogen lights were only activated five times during the three days, and on four occasions it was due to users blocking the workstations' light sensors. The total amount of time that the halogen lights were switched on was less than 30 minutes. An example of the BAS controller applying the light management control rules is shown in figures 5.34 and 5.35. The controller started by setting the Lifx light's brightness to the maximum level, on the next controller steps, the light's brightness was set to a level that kept the workstation level higher very close to the five hundred lux set by the user as his preferred light level. When the occupant left the office at 12h34m to have lunch, the controller turned off the light.

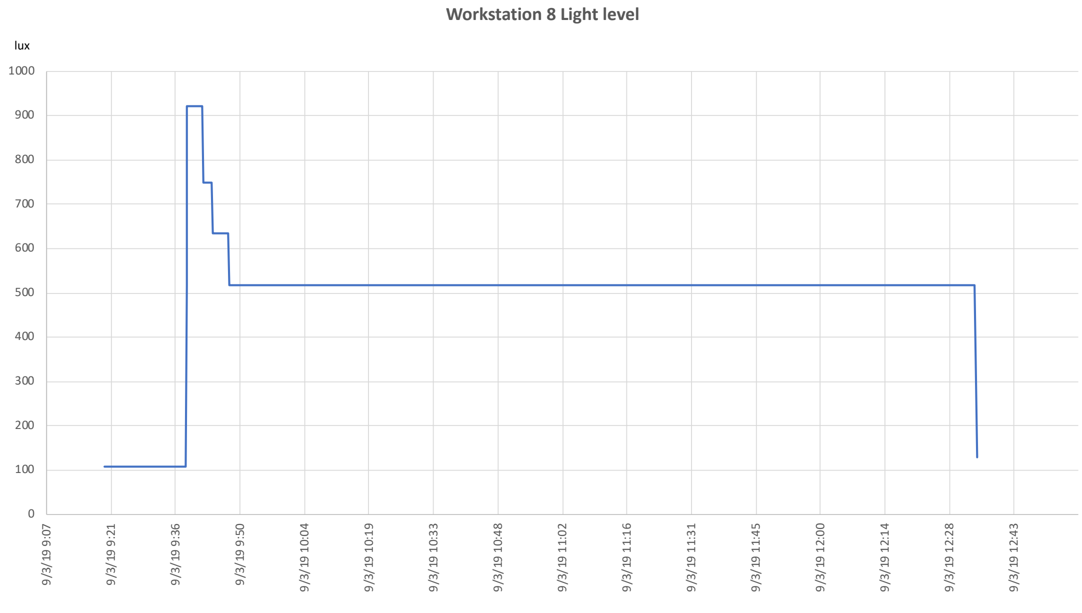

Figure 5.34: Workstation 8 light level variation

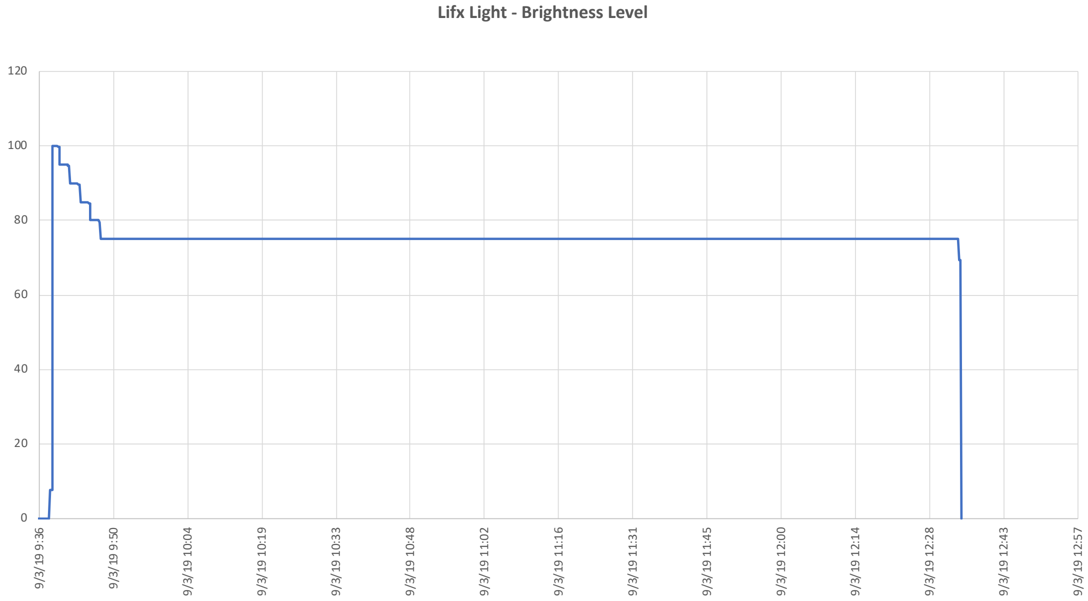

Figure 5.35: Workstation 8 Lifx light brightness variation

5.5.3 User survey

Three users replied[6] to the survey[7]. 66% are women, and the age average is 24,6 years and 66% reported as having myopia. Users provided the following feedback regarding the environmental conditions and the BAS controller operation during the three days:

- 100% of the users found the office's temperature adequate.
- When arriving at the office 66% of the users found the office's temperature as adequate, while 33% classified the temperature between adequate and hot.
- Users were asked to classify the controller's management of the office temperature. On a scale of zero to four with zero meaning a negative evaluation of the system operation and four meaning a positive evaluation, 100% of the users scored the system operation with a value of three.
- 66% of the users found the office's light level as adequate and 33% assessed the light level between adequate and excessive.
- Users were asked to classify the controller's management of the office's light level. On a scale of zero to four with zero meaning a negative evaluation of the system operation and four meaning a positive evaluation, 33% of the users scored the system operation with a value of four, 33% scored the system operation with a value of three and 33% of the users scored the system operation with a value of two.

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[6] https://joao980917.typeform.com/report/wdCUf9/T6MovgVJZmtlcuEV (accessed 25-03-2019)

[7] https://joao980917.typeform.com/to/wdCUf9 (accessed 25-03-2019)

- Users were invited to rate the effect that the BAS had on their work. On a scale of zero to four with zero meaning a negative effect of the system operation and four meaning a positive effect, 33% rated the effect with a four value, 33% rated the effect with a with a value of three and 33% rated the effect with a value of two.

Comparing with the feedback received from the first study, a higher percentage of users classified the office's temperature when they arrived at the office as adequate. It is possible that having users more satisfied at the time of arrival, be an answer to why the heaters were not used during this empirical study.

5.6 Third Empirical study

On the third empirical study, the BAS controller builds up from the version implemented in the previous study. Now the BAS does not consider humans as being confined to the CPS plant, and to perform supervisory control. Humans are viewed as capable of performing the sensor and actuator CPS feedback loop roles. They can provide assessments regarding the office environment, the Open Aquarium system, the state of actuators that are not automated. The Smartlab case study relies on low cost-oriented IoT solutions for sensing and actuation. The reliability, resiliency and accuracy of these components are usually not up to the level offered by industrial-grade solutions.

The Open Aquarium fish feeder has a capacity for fish food that only lasts for a few days. The system is not capable of determining the amount of food that it is available, and it will perform the feed operation regardless if there is any food left. Human intervention is necessary to refill the feeder. Also since the aquarium is an add-on to an existing aquarium, it is not possible for the system to know if the sensors and actuators remain placed at the planned places. Humans can provide an additional layer of resiliency and reliability to the system by performing sensing tasks. When combined with the existing automated sensor data, the human assessment of the CPS plant can help in the identification of situations where sensors fail or are miscalibrated. The controller with the objective of increasing the users' comfort and thus reducing the number of actions that might result in the waste of energy, takes as input the users feedback regarding the temperature and light conditions. Before starting the test users were informed that their feedback would be taken into account by the CPS controller when setting the temperature and light conditions. The occupants can provide their using the mobile application's feedback interface presented in figure 4.24.

In industrial manufacturing, operations scheduling is an important factor [16] to achieve sustainable manufacturing operations. However, in the second empirical study, our approach to schedule the controller actions in an human-centric system, based on a user fixed schedule contributed to the waste of energy. In this controller version, users were asked to provide the information if they plan to work at the office the next day and they were free to change their intended time of the arrival at the laboratory. Our goal to reduce the number of occasions that the BAS pre-heats the room when the users are already aware that they cannot comply with the schedule that they initially chose.

The occupants can also perform tasks that will improve the existing conditions like opening a window when the indoor temperature is too hot while the outdoor temperature is lower. The assignments can result in energy savings or the improvement of the existing temperature and light conditions. In this test, humans were asked to perform the following tasks:

- Open and close windows. Before the test started, users were informed that the last user exiting the laboratory should close all the windows.
- Refill the fish feeder.
- Check the aquarium water temperature. To complete this task, users check visually the temperature registered by the thermometer that is installed in the aquarium, and insert the readed value in the Smartlab mobile application.

Considering that we are dealing with a retrofitting scenario and the cost of replacing the room's windows is considered too high, a possible alternative to not rely on humans assessments if a window is open or not, would be the installation of low-cost sensors that could detect if a window is open or closed. Additionally, if a wind direction sensor could be installed, we believe that this would provide the BAS controller with valuable information that would result in more effective control decisions. The controller could decide which window to open, on which side of the building based on wind direction and the occupants' room location. An analysis would have to be performed to determine if this would result in additional energy savings and the impact in the room users' comfort.

The number of tasks that could be assigned to a user in a two hours period was limited to one. For each task received the users were able to indicate that they completed the task or if they decided to not complete the assignment required by the BAS controller. The goal was not to overburden the occupants with tasks while they are focused on working. All the tasks shared a thirty minutes timeout. In situations were a timeout exists, the task is reassigned to another occupant.

Considering the control rules set presented in section 5.5.1 and the controller step defined for one minute, the following changes were implemented:

- Temperature - in each controller step, the average of the users' temperature feedbacks is calculated. The possible outcomes are minus one when the users desire a lower room temperature, zero if they consider the temperature as adequate or one if they wish a higher room temperature. The users' feedback result is added to the controller calculated temperature. If there are users that can receive an open window task, and it is earlier than 17h00m then the controller creates a new task. When the last user exits the room the number of open windows is reset to zero.

- Light - At each controller step, the system checks for each user their unprocessed feedbacks. The system adds or subtracts 10% to the users preferred light level if the users consider that more or less light is needed. Like the first two empirical studies, the controller calculated light level must comply with the legally defined targets.
- Aquarium tasks - If there are users available to perform tasks, the system requires during the morning and in the afternoon the users' assessment of the aquarium water temperature. Once a day the controller creates a task for one user to refill the aquarium fish feeder. A higher priority was assigned to the aquarium water temperature related tasks.

5.6.1 Collected Data

During the three days of testing, the sky was partially clouded, the outdoors luminosity pattern was similar throughout the three days, and the temperature varied from a minimum value of 8,81°and a maximum value of 20,19°. The outdoors temperature and luminosity variation during the test period are presented in figures 5.36 and 5.37 respectively.

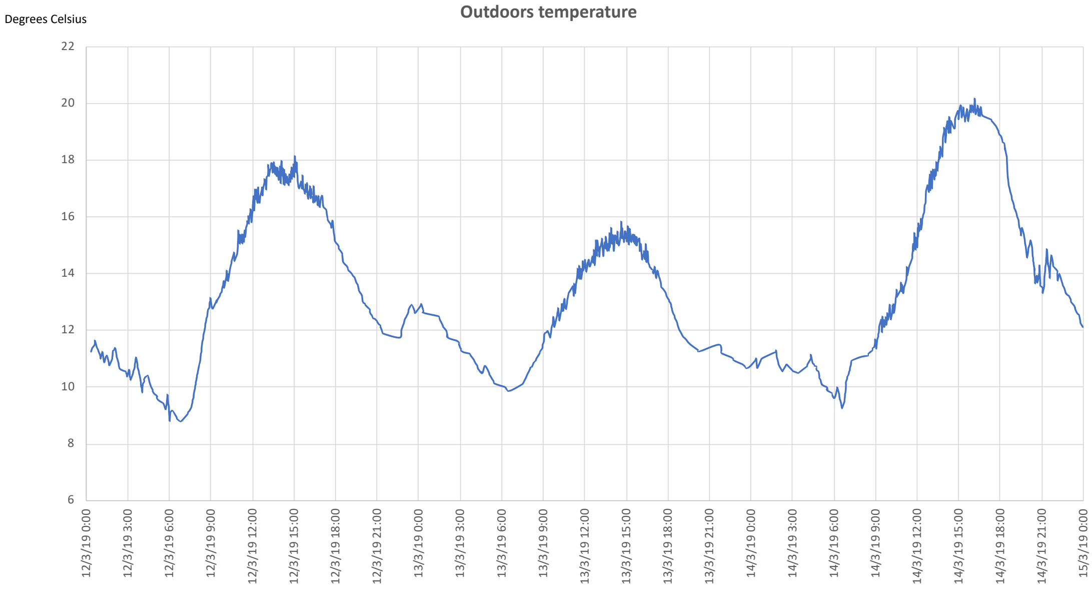

Figure 5.36: Outdoors temperature variation during the three days test

Throughout the time of the test, the BAS infrastructure consumed a total of 32.53kWh. The energy expenditure variation between the three days of testing and the breakdown of the energy totals between the AC unit and the rest of the BAS's devices is presented in figure 5.38.

By allowing the occupants to update their working schedule enabled to react to a similar situation that occurred on the second empirical study's last day. When the second test ended, workstation one's user indicated that would arrive at 12h40m and arrived at 12h41m. Workstations four, six and eight provided the information that they would arrive during the afternoon. By activating the AC unit at 11h40m, the equipment was turned on 4h35m later than it would have been if the system assumed the user arrival time 8h05m indicated for the test's first day. In this situation, the system has benefited from having humans performing the CPS feedback loop role of sensors. The occupants acted as sensors of their expected presence at the office. Alternatively, the CPS could infer the predicted arrival of users to the laboratory by accessing the users' smartphone Global Positioning System (GPS) sensor data and then apply geofencing techniques, but as privacy concerns grow, the systems relying on the location data to operate have to obtain the user's permission before they have access to their position data. Having humans providing their predicted schedule could present an alternative to HiTLCPSs to react to the humans' arrival or departure to the systems plant. We leave as future work the study of the reliability of having humans performing this role in systems with sustainability goals. Gamification techniques [54] that have the objective to keep the users engaged with these systems and, decision fatigue [5] avoidance approaches should also be analysed.

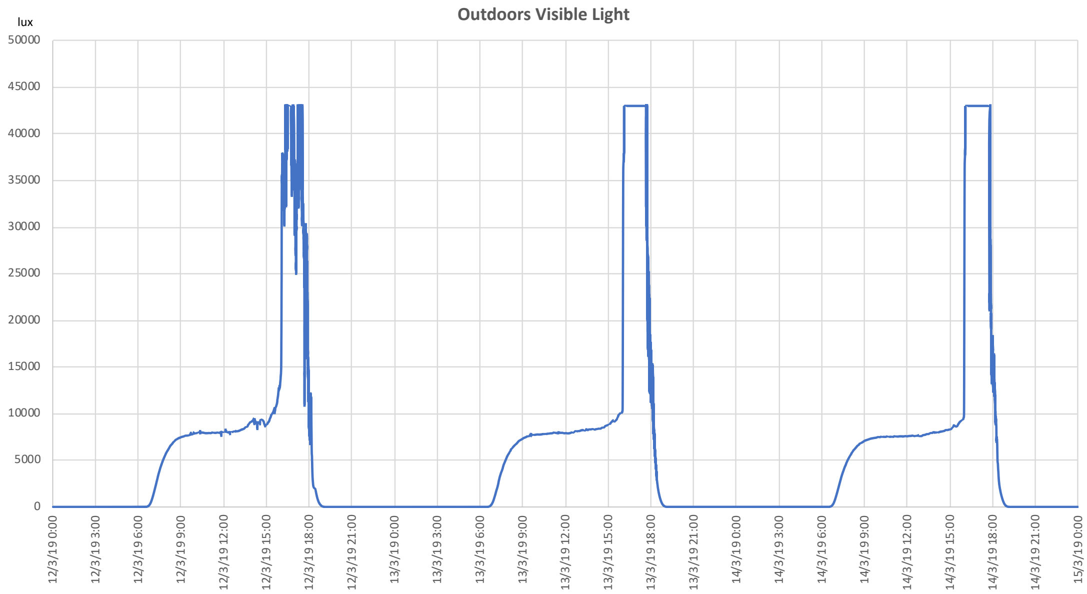

Figure 5.37: Outdoors visible light variation during the test

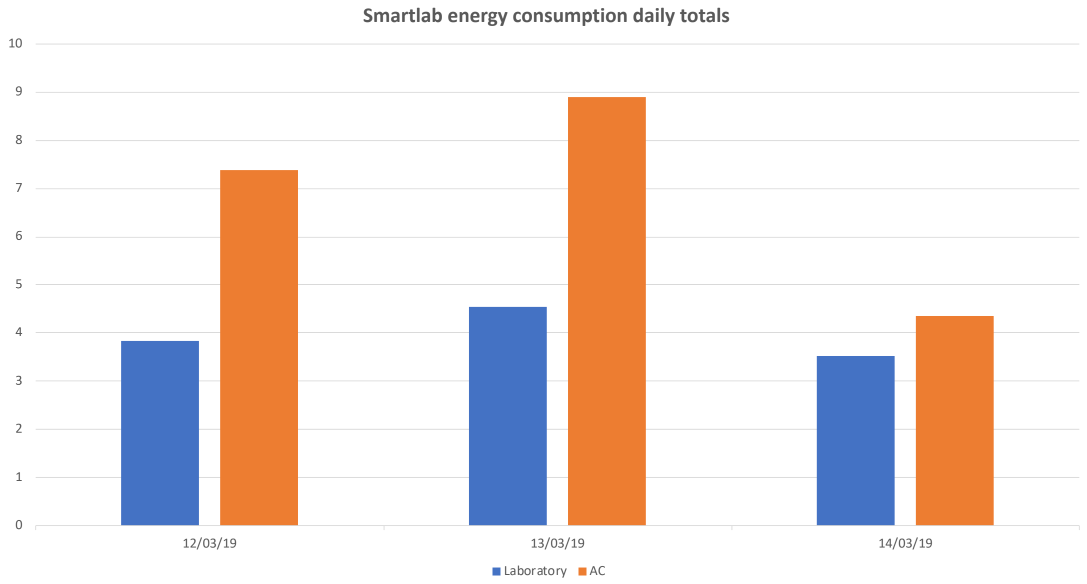

Figure 5.38: Smartlab daily energy consumption

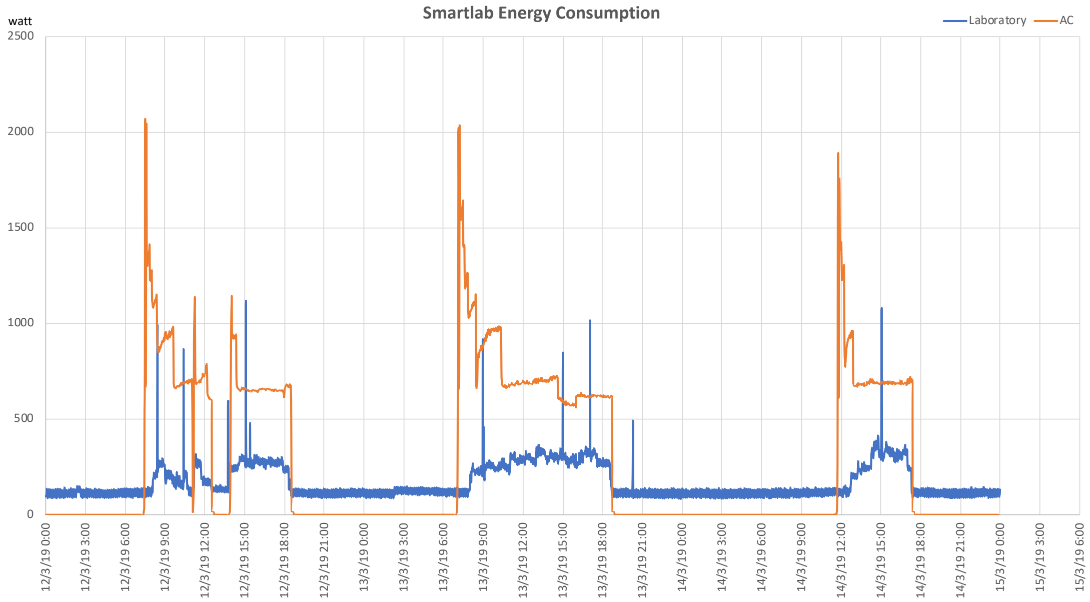

Figure 5.39: Power consumption variation during the test. No halogen lights or personal heaters were activated

Throughout the study, the BAS system assigned to users fifteen tasks and users submitted seventeen feedbacks. All the assigned tasks were completed, and as such, no decay in the users' engagement with the system was noticed. After the users signalled the system that the task was completed, there was a visual confirmation if the task was finished correctly. For tasks where the users were asked to check the aquarium water temperature, there was a verification if the supplied temperature was correct, in the fish feeder refill operations, the fish feeder 's assembly and placement was verified, and finally, for opening and closing windows tasks, the windows were checked if the user performed the task successfully. The users completed all the tasks successfully. Still, the time that users needed to complete ranged from thirty seconds to nine minutes. The uncertainty of the tasks' completion time presents a challenge for BAS controllers as task expiration periods have to be defined. If there are other automated actuators available, the decision of using an actuator that presents a higher energy cost has to be made at every controller update step.

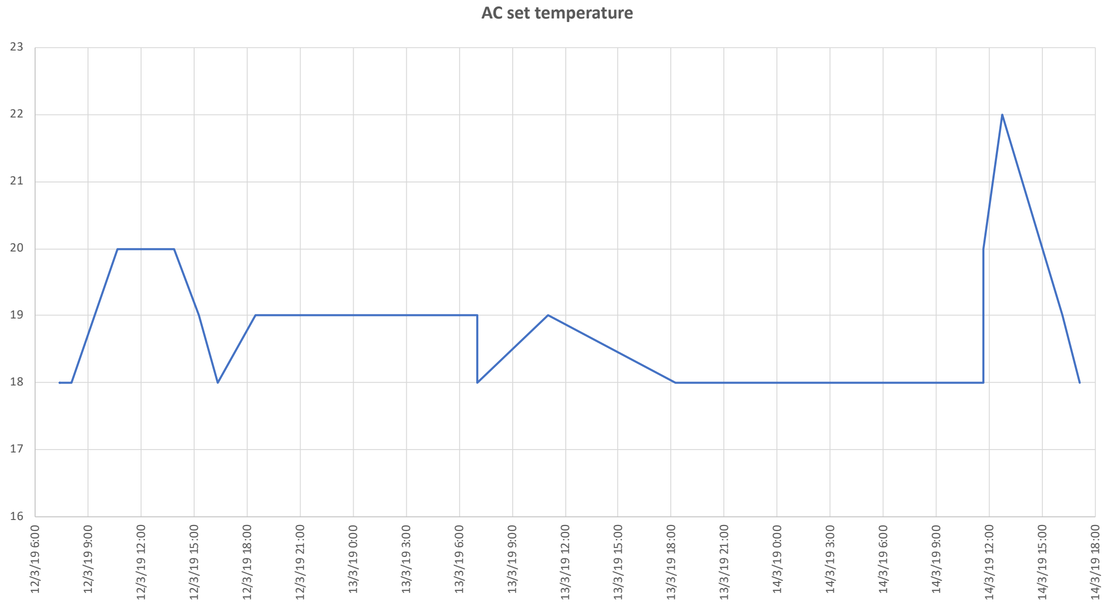

Figure 5.40: AC temperature variation. The users' feedback is an input parameter on the calculation of AC set temperature

On thirteen feedbacks, users classified the temperature and light level conditions as adequate. On two occasions, workstation two's user indicated that it wanted an increase in the room's temperature and the same user on one occasion indicated that it wanted a cooler room temperature. As mentioned before, the controller used the users' feedback as an input parameter when calculating the appropriate temperature and light levels. On the first day, at 15h39m workstation two's user indicated his preference for a cooler temperature. The user's preferred temperature was 20°and at the feedback submission time, workstation two's temperature was 20.75°. In figure 5.40 it is shown that the controller due to an average room temperature of 21°had reduced the AC temperature set point to 19°at 15h17m. As there were users in the room and the last AC unit setpoint update had occurred less than sixty minutes the controller could not set a new AC temperature setpoint until 16h17m. At 16h18m the controller taking workstation two's user feedback into account changed the equipment setpoint to 18°. Additionally, in the first controller update step after the user submitted his feedback, workstation eight's user was assigned with the task of opening a window because at that moment,the outdoors temperature was inferior to the indoor temperature. As shown in figure 5.41 the workstations temperature kept rising despite the controller actions. In the future, it will be required a deeper understating of the room's thermal model and the available AC equipment's settings to increase the controller temperature management effectiveness.

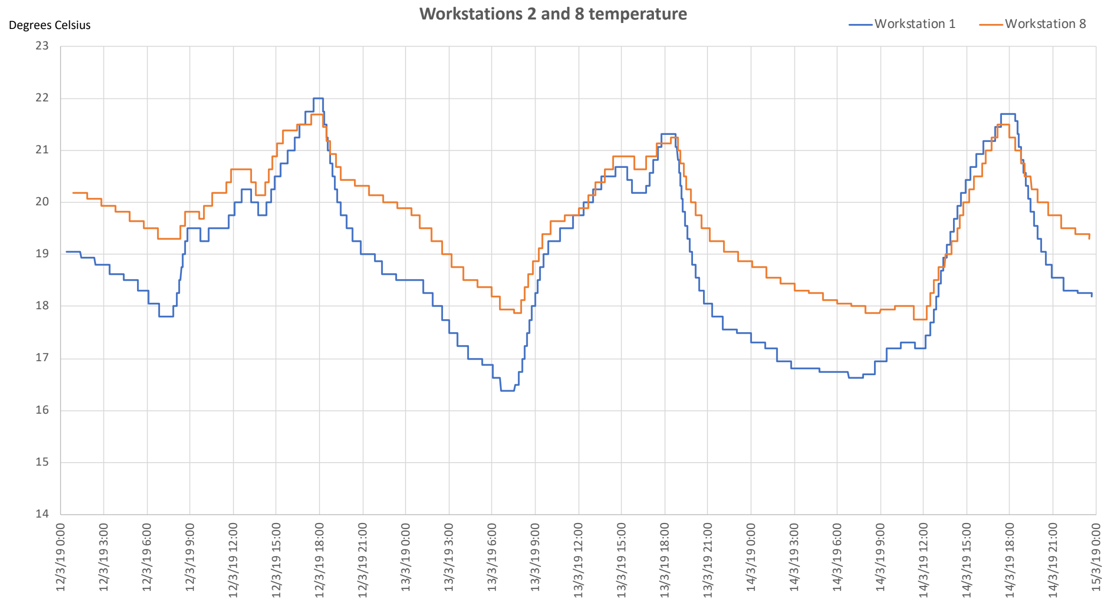

Figure 5.41: Workstations 2 and 8 temperature variation

The controller also considered the user light level feedbacks during light level management. On the study's last day, workstation four's user arrived at 14h22m and exited the office at 17h19m. At the time of arrival, the user's workstation light level was 259 lux. Considering the user's preferred light level of five hundred lux and the control rules presented in section 5.5.1 the controller at each step incremented the LED light's brightness by 15% until the users preferred light was reached. The workstation four light level variation and the Lifx LED light's brightness variation are presented in figures 5.42 and 5.43 respectively. At 14h28m workstation four's user submitted feedback where he indicated that a higher light level was needed. The controller was by this time increasing the LED light's brightness progressively, and at the first controller update step after the user's feedback, the controller increased the user preferred light level by 10% for the rest of the day.

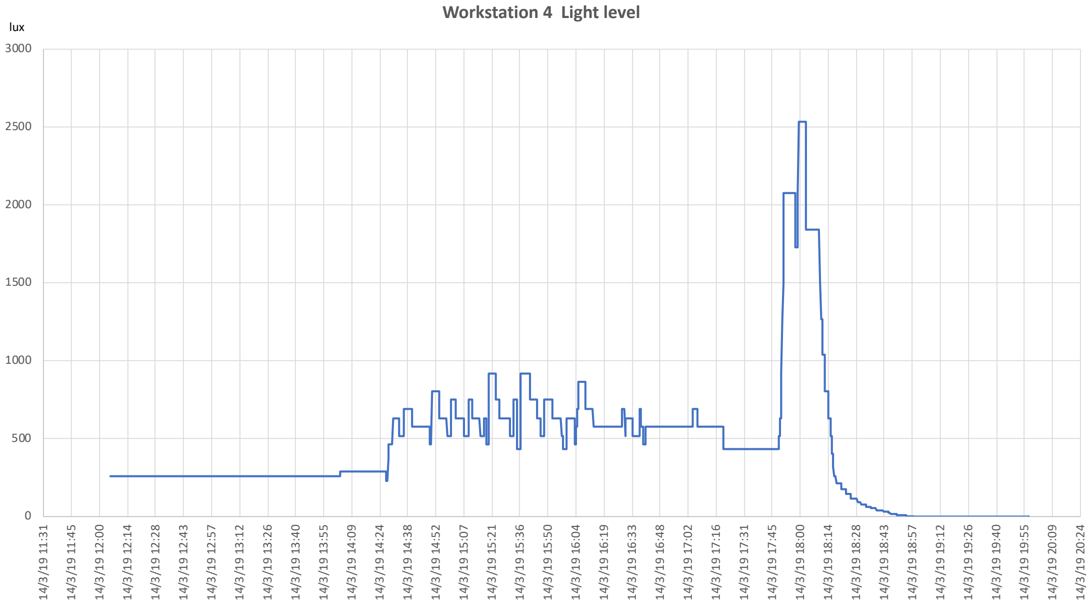

Figure 5.42: Workstation 4 light level variation

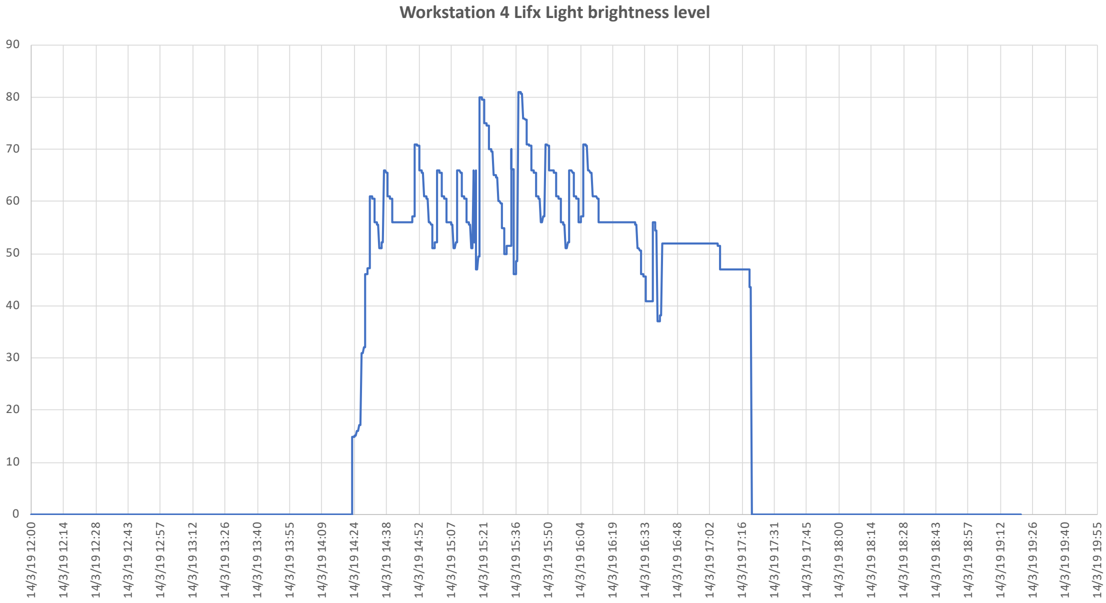

Figure 5.43: Workstation 4 LED light's brightness variation that was necessary to maintain the 500 lux recommended level

Throughout the test, the controller did not activate the halogen lights installed at the ceiling. This resulted in additional energy savings. The use of the workstations' LED light maintained the users working under light conditions close to their preferences for the vast majority of the time.

Finally, we present justifications for the sudden surges on Smartlab's energy consumption that are visible in figure 5.39. The activation of the coffee machine explains eight of the nine power spikes. The remaining energy consumption surge occurred on the second day at 20h18m due to manual activation of one of the halogen lights performed by maintenance or security personnel.

To activate the coffee machine, workstation eight's user clicked on the coffee cup icon available on the mobile application home interface presented in figure 4.21. When the BAS controller receives the user's command, the coffee machine is activated for two minutes. Our goal was to achieve energy savings in equipment that are used by several users. To evaluate the effectiveness of this approach a three-day test is not sufficient; we leave as future work the execution of a more extended study.

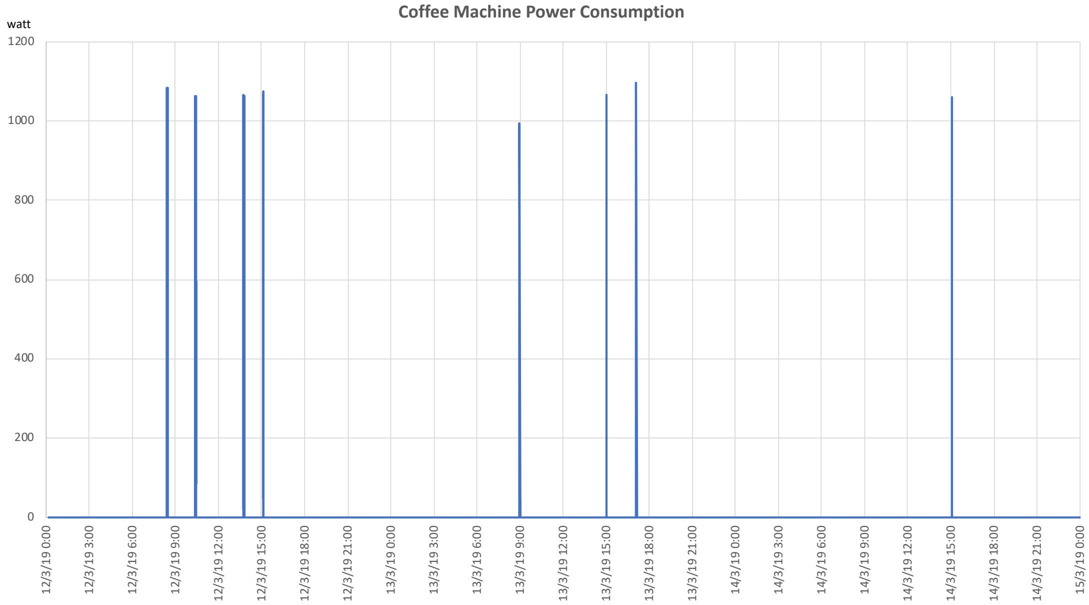

Figure 5.44: Coffee machine power consumption

5.6.2 User survey

The same group of users that replied to the second empirical survey presented in section 5.5.3, replied to the third empirical poll[8]. Users provided the following feedback[9] regarding the environmental conditions and the BAS controller operation during the three days:

- 100% of the users found the office's temperature adequate throughout the study.
- When arriving at the office 100% of the users described the office's temperature as adequate.
- Users were asked to classify the controller's management of the office temperature. On a scale of zero to four with zero meaning a negative evaluation of the system

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[8] https://joao980917.typeform.com/to/aUqhgE (accessed 25-03-2019)

[9] https://joao980917.typeform.com/report/aUqhgE/uRixjrVL7pic9Hz3 (accessed 25-03-2019)

operation and four meaning a positive evaluation, 66% of the users scored the system operation with a value of four, and 33% scored it with a value of three.

- 100% of the users found the office's light level as adequate throughout the test.
- Users were asked to classify the controller's management of the office's light level. On a scale of zero to four with zero meaning a negative evaluation of the system operation and four meaning a positive evaluation, 100% of the users scored the system operation with a value of four.
- Users were invited to rate the effect that the BAS had on their work. On a scale of zero to four with zero meaning a negative effect of the system operation and four meaning a positive effect, 66% rated the effect with a four value and 33% rated the effect with a with a value of three.
- 100% of the users classified the number of tasks required by the system not excessive.

Considering the survey responses given by users on all the performed empirical studies, the users presented higher levels of satisfaction towards the environmental conditions offered by the system, when the BAS controller considered humans as system components. In this study, humans participated as sensors, actuators and they were part of the CPS plant. The higher users' comfort levels did not result from controller decisions that produced energy waste. The collected data shows that the Smartlab HiTLCPS presented a more energy efficient operation while providing more comfortable conditions to the laboratory's occupants.

5.7 Threats to validity

As mentioned in the previous sections the Smartlab project is running on an academic computer science laboratory. The laboratory' occupants are not obligated to comply with a working schedule. Some users are full-time students; some have teaching duties, and some are student workers. For these reasons, it was challenging to find a group of users that could come to work at the office for more than three consecutive days.

Due to time restriction challenges previously mentioned, it was not possible to perform a system commissioning process. The absence of an extended user training period had effects on the second empirical study first morning, where users were not acquainted with the solution. Situations occurred, where the users covered the workstations light sensors and left their smartphones inside the room when exiting the room.

Three empirical studies were conducted during the work that we present. To be able to compare the studies collected data, the outdoor environmental conditions had to be similar between tests. Considering all the existing restrictions, the empirical studies duration had to be restricted to three days. The empirical studies took place at the transition from winter to spring, as the conditions change throughout the year, it will be essential to test the different BAS configurations, for extended periods to evaluate if the gains of considering humans as system components are changed and to achieve statistically significant results.

During the empirical studies, the controller used the indoor location system presented in section 4.3.2 to determine if the system users were at the office. Generally, the solution worked as expected except on four occasions. Three false negatives occurred when the workstations two and six users smartphones entered the energy saving mode. Upon entering the energy mode, the Android operating system killed the indoor location system's background service, and the mobile application notified the controller that the users were not at their workstation. Users were aware that the system experienced an unexpected error because the BAS controller switched off their workstation's LED light. To overcome this problem, the users were asked to use mobile application to manually notify the system when they entered and exited the office and to restart the mobile application when their smartphones exited the energy saving mode.

One false positive happened during the third empirical when workstation two's user had a meeting on an office below the user's workstation. The indoor location system was configured to assume that users were at their workstations when the users were at a distance inferior to four meters from the beacon associated with their workstation. The situation was detected, and the user was asked to use the mobile application to inform the BAS that he was not near his workstation. Afterwards, the workstation zone radius was reduced to three meters.

Finally, we should indicate that three office occupants that participated in the empirical studies are working on the Smartlab project. Due to their involvement in the project, there could be effects on their engagement levels.

Chapter 6

Conclusions

6.1 Summary

The goal of this work was to demonstrate that a BAS CPSs designed to consider the Human in the Loop, therefore participatory, with predefined roles, as if a system component, are more energy efficient while providing the adequate temperature and light conditions. We started with a room commissioning process where we study the studied the effect of the different room components on the BAS goals. Although our findings were supported with a small quantity of statistical data, we proceeded to the implementation of three pilot studies with the objective to prepare a systematic study that will have a previewed duration of one year. An analysis was made of the current legal framework applied to environmental conditions at the workplace that was followed by a review of the effects on the workers' health and productivity while working in inappropriate conditions. In the first study, the laboratory did not include automation, in the second study a BAS controller was responsible for applying the legally defined temperature and light conditions with human participating only as CPS plant elements, in the third study the BAS required humans to play different roles that are key factors in the system achieving its goals. On the third empirical study, we addressed the importance of maintaining high levels of humans engagement with the system. We were able to implement a controlled environment that deals with the heterogeneity of the various IoT deployed. During the writing period of this thesis, we published this work [8], and it will become a chapter in a book [1] to be published until the end of 2019.

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[1] Bedir Tekinerdogan, Dominique Blouin, Miguel Goulão, Paulo Carreira, Vasco Amaral, Hans Vangheluwe "Multi-Paradigm modelling for cyber-physical systems", Elsevier

6.2 Future Work

We intend to proceed with more extended in time studies where the various weather seasons conditions and different office users profiles will allow us to achieve statistically significant results.

Strategies to keep human participation in HiTLCPS at high levels are essential for the system to achieve its goals. We plan to introduce gamification strategies to maintain the system reliability on human involvement in different roles of the CPS feedback loop.

Explore modelling, simulation and introduce verification tools and techniques at the domain abstraction level before proceeding to deployment or system reconfigurations.

Finally, we would like to study the impact on the BAS's performance when feedforward neural networks are introduced in the controller's operation with the objective to reduce the statistical uncertainty that results from the BAS dependability on human participation.

BIBLIOGRAPHY

[1] Y Aguiar, M Vieira, and E. Galy. "Refining a user behaviour model based on the observation of emotional states." In: *COGNITIVE 2011 : The Third International Conference on Advanced Cognitive Technologies and Applications Refining* c (2011), pp. 36–40. DOI: `10.13140/RG.2.1.1305.2646`. URL: `http://www.thinkmind.org/index.php?view=article{\&}articleid=cognitive{\_}2011{\_}2{\_}20{\_}40073`.

[2] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash. "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications." In: *IEEE Communications Surveys and Tutorials* 17.4 (2015), pp. 2347–2376. ISSN: 1553877X. DOI: `10.1109/COMST.2015.2444095`. arXiv: `arXiv:1011.1669v3`.

[3] E. Annunziata, M. Frey, and F. Rizzi. "Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe." In: *Energy* 57 (2013), pp. 125–133. ISSN: 03605442. DOI: `10.1016/j.energy.2012.11.049`. URL: `http://dx.doi.org/10.1016/j.energy.2012.11.049`.

[4] J. R. Anshel. "Visual ergonomics in the workplace." In: *AAOHN journal : official journal of the American Association of Occupational Health Nurses* 55.10 (2007), 414–20; quiz 421–2. ISSN: 0891-0162. URL: `http://www.ncbi.nlm.nih.gov/pubmed/17969539`.

[5] R. F. Baumeister and K. D. Vohs. "Self-Regulation and the Executive Function of the Self." In: *Handbook of Self and Identity*. Ed. by M. R. Leary and J. P. Tangney. Guilford Press, 2003, pp. 1–197.

[6] M. R. Brambley, D Hansen, P Haves, D. R. Holmberg, S. C. McDonald, K. W. Roth, and P Torcellini. "Advanced sensors and controls for building applications: Market assessment and potential R&D pathways." In: *Pacific Northwest National Laboratory* (2005).

[7] M Brettel, N Friederichsen, and M Keller. "How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective." In: *International Journal of* 8.1 (2014), pp. 37–44. ISSN: 1307-6892. DOI: `scholar.waset.org/1999.8/9997144`. URL: `http://www.waset.org/publications/9997144`.

[8] J. Cambeiro, C. Gomes, V. Amaral, A. Rodrigues, and J. Cunha. “A building automation case study setup and challenges.” In: *Proceedings of the 4th International Workshop on Software Engineering for Smart Cyber-Physical Systems - SEsCPS ’18*. New York, New York, USA: ACM Press, 2018, pp. 41–44. ISBN: 9781450357289. DOI: `10.1145/3196478.3196482`. URL: `http://dl.acm.org/citation.cfm?doid=3196478.3196482`.

[9] A. A. Cardenas, S. Amin, and S. Sastry. “Secure control: Towards survivable cyber-physical systems.” In: *Proceedings - International Conference on Distributed Computing Systems* (2008), pp. 495–500. ISSN: 1545-0678. DOI: `10.1109/ICDCS.Workshops.2008.40`.

[10] CEN. “DIN EN 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.” In: (2006), p. 52.

[11] CENELEC. “ÖNORM EN 12464-1 Light and lighting – Lighting of work places Part 1 : Indoor work places.” In: 1 (2003), pp. 1–43.

[12] V. K. Diddi and S. B. Jamge. “A Vision Based System for Monitoring the Loss of Attention in Automotive Drivers.” In: 4.7 (2015), pp. 2013–2016.

[13] R. Drath and A. Horch. “Industrie 4.0: Hit or hype? [Industry Forum].” In: *IEEE Industrial Electronics Magazine* 8.2 (2014), pp. 56–58. ISSN: 19324529. DOI: `10.1109/MIE.2014.2312079`.

[14] A Fernbach, W Granzer, and W Kastner. “Interoperability at the management level of building automation systems: A case study for BACnet and OPC UA.” In: *ETFA2011*. 2011, pp. 1–8. DOI: `10.1109/ETFA.2011.6059106`.

[15] B. P. Fremantle. “WHITE PAPER A Reference Architecture For The Internet of Things 2 . The Internet of Things – An Overview.” In: (2016).

[16] A. Giret, D. Trentesaux, and V. Prabhu. “Sustainability in manufacturing operations scheduling: A state of the art review.” In: *Journal of Manufacturing Systems* 37 (2015), pp. 126–140. ISSN: 02786125. DOI: `10.1016/j.jmsy.2015.08.002`. URL: `http://dx.doi.org/10.1016/j.jmsy.2015.08.002`.

[17] C. Gomez, J. Oller, and J. Paradells. “Overview and evaluation of bluetooth low energy: An emerging low-power wireless technology.” In: *Sensors (Switzerland)* 12.9 (2012), pp. 11734–11753. ISSN: 14248220. DOI: `10.3390/s120911734`.

[18] HSE. *Lighting at work Health and Safety Executive*. Vol. 38. 1987, pp. 5–11. ISBN: 9780717612321. URL: `http://www.hse.gov.uk/pubns/priced/hsg38.pdf`.

[19] N Jazdi. “Cyber physical systems in the context of Industry 4.0.” In: *2014 IEEE Automation, Quality and Testing, Robotics* (2014), pp. 2–4. DOI: `10.1109/AQTR.2014.6857843`. URL: `http://ieeexplore.ieee.org/xpls/abs{\_}all.jsp?arnumber=6857843`.

[20] V. Karagiannis, P. Chatzimisios, F. Vazquez-Gallego, and J. Alonso-Zarate. "A Survey on Application Layer Protocols for the Internet of Things." In: *Transaction on IoT and Cloud Computing* 3.1 (2015), pp. 11–17. ISSN: 2331-4761. DOI: 10.5281/ZENODO.51613. URL: http://icas-pub.org/ojs/index.php/ticc/article/view/47.

[21] M. Kay, E. K. Choe, J. Shepherd, B. Greenstein, N. Watson, S. Consolvo, and J. a. Kientz. "Lullaby: a capture & access system for understanding the sleep environment." In: *Proceedings of the 2012 ACM Conference on Ubiquitous Computing - UbiComp '12* (2012), pp. 226–234. DOI: 10.1145/2370216.2370253. URL: http://dl.acm.org/citation.cfm?id=2370216.2370253.

[22] A. Kleppe. *Software language engineering: creating domain-specific languages using metamodels*. Pearson Education, 2008.

[23] E. G. Landis, V. Yang, D. M. Brown, M. T. Pardue, S. A. Read, and W. H. Coulter. "Clinical and Epidemiologic Research Dim Light Exposure and Myopia in Children." In: (2018), p. 1670. ISSN: 1552-5783. DOI: 10.1167/iovs.18-24415. URL: https://doi.org/.

[24] E. A. Lee. "Cyber Physical Systems: Design Challenges." In: *2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)* (2008), pp. 363–369. ISSN: 1555-0885. DOI: 10.1109/ISORC.2008.25. URL: http://ieeexplore.ieee.org/document/4519604/.

[25] E. A. Lee and S. A. Seshia. *Introduction to Embedded Systems - A Cyber-Physical Systems Approach*. 2017, pp. 1–519. ISBN: 978-0-262-53381-2.

[26] G. Lilis, G. Conus, N. Asadi, and M. Kayal. "Towards the next generation of intelligent building: An assessment study of current automation and future IoT based systems with a proposal for transitional design." In: *Sustainable Cities and Society* 28 (2017), pp. 473–481. ISSN: 2210-6707. DOI: \url{http://dx.doi.org/10.1016/j.scs.2016.08.019}.

[27] Y. Liu, M. Li, D. Yang, X. Zhang, A. Wu, S. Yao, Z. Xue, and Y. Yue. "Closed-loop control better than open-loop control of profofol TCI guided by BIS a randomized, controlled, multicenter clinical trial to evaluate the CONCERT-CL closed-loop system." In: *PLoS ONE* 10.4 (2015), pp. 1–12. ISSN: 19326203. DOI: 10.1371/journal.pone.0123862. URL: http://dx.doi.org/10.1371/journal.pone.0123862.

[28] J. Lu, T. Sookoor, V. Srinivasan, G. Gao, B. Holben, J. Stankovic, E. Field, and K. Whitehouse. "The Smart Thermostat: Using Occupancy Sensors to Save Energy in Homes." In: *Proceedings of ACM SenSys* 55 (2010), pp. 211–224. DOI: 10.1145/1869983.1870005. URL: http://www.cs.virginia.edu/{~}stankovic/psfiles/sensys10-final169.pdf.

[29] K. E. Mary Reena, A. Theckethil Mathew, and L. Jacob. "An Occupancy Based Cyber-Physical System Design for Intelligent Building Automation." In: *Mathematical Problems in Engineering* 2015 (2015). ISSN: 15635147. DOI: 10.1155/2015/132182.

[30] B. L. Moore. "Reinforcement Learning for Closed-Loop Propofol Anesthesia : A Study in Human Volunteers." In: *Acm Jmlr* 15 (2014), pp. 655–696. ISSN: 1532-4435.

[31] S. Munir, J. a. Stankovic, C.-J. M. Liang, and S. Lin. "Cyber Physical System Challenges for Human-in-the-Loop Control." In: *The 8th International Workshop on Feedback Computing* (2013).

[32] P. S. Myles, K. Leslie, J. McNeil, A. Forbes, and M. T. Chan. "Bispectral index monitoring to prevent awareness during anaesthesia: The B-Aware randomised controlled trial." In: *Lancet* 363.9423 (2004), pp. 1757–1763. ISSN: 01406736. DOI: 10.1016/S0140-6736(04)16300-9.

[33] T. T. Norton and J. T. S. Jr. "NIH Public Access." In: 205 (2014), pp. 48–57. ISSN: 1096-0007. DOI: 10.1016/j.exer.2013.05.004.Light.

[34] K. Ohashi, O. Dalleur, P. C. Dykes, and D. W. Bates. "Benefits and Risks of Using Smart Pumps to Reduce Medication Error Rates: A Systematic Review." In: *Drug Safety* 37.12 (2014), pp. 1011–1020. ISSN: 11791942. DOI: 10.1007/s40264-014-0232-1.

[35] S. Perera. "Iot analytics: using big data to architect iot solutions." In: *WS02 White Paper* (2015).

[36] K. Pohl, G. Böckle, and F. Van Der Linden. *Software product line engineering: Foundations, principles, and techniques.* 2005, pp. 1–467. ISBN: 3540243720.

[37] G. D. Puri, P. J. Mathew, I. Biswas, A. Dutta, J. Sood, S. Gombar, S. Palta, M. Tsering, P. L. Gautam, A. Jayant, I. Arora, V. Bajaj, T. S. Punia, and G. Singh. "A Multicenter Evaluation of a Closed-Loop Anesthesia Delivery System: A Randomized Controlled Trial." In: *Anesthesia and Analgesia* 122.1 (2016), pp. 106–114. ISSN: 15267598. DOI: 10.1213/ANE.0000000000000769.

[38] R. Rajkumar, I. Lee, L. Sha, and J. Stankovic. "Cyber-physical systems: The next computing revolution." In: *47th ACM/IEEE Design Automation Conference (DAC)* (2010), pp. 731–736. ISSN: 0738-100X. DOI: 10.1145/1837274.1837461.

[39] J. A. Reboso, J. A. Maéndez, H. J. Reboso, and A. M. León. "Design and implementation of a closed-loop control system for infusion of propofol guided by bispectral index (BIS)." In: *Acta Anaesthesiologica Scandinavica* 56.8 (2012), pp. 1032–1041. ISSN: 00015172. DOI: 10.1111/j.1399-6576.2012.02738.x.

[40] P. Runeson and M. Höst. "Guidelines for conducting and reporting case study research in software engineering." In: *Empirical Software Engineering* 14.2 (2008), p. 131. ISSN: 1573-7616. DOI: 10.1007/s10664-008-9102-8. URL: https://doi.org/10.1007/s10664-008-9102-8.

[41] W. Seppanen, O. Fisk and Q. Lei. "Room Temperature and Productivity in Office Work." In: (2006).

[42] D. S. Sousa Nunes, P. Zhang, and J. Sa Silva. "A Survey on human-in-The-loop applications towards an internet of all." In: *IEEE Communications Surveys and Tutorials* 17.2 (2015), pp. 944–965. ISSN: 1553877X. DOI: 10.1109/COMST.2015.2398816.

[43] H. Vangheluwe, J. De Lara, and P. J. Mosterman. "An introduction to multi-paradigm modelling and simulation." In: *Proceedings of the AIS'2002 conference (AI, Simulation and Planning in High Autonomy Systems), Lisboa, Portugal.* 2002, pp. 9–20.

[44] V. P. I. Virginia Tech and S. University. *Workplace ergonomics program.* 2001, pp. –. ISBN: 5402318751. URL: http://www.ehs.vt.edu.

[45] N. S. Wales. *THE IMPACT OF MYOPIA.* March. 2015. ISBN: 9789241511193.

[46] S. Wang, G. Zhang, B. Shen, and X. Xie. "An integrated scheme for Cyber-physical building energy management system." In: *Procedia Engineering* 15.0 (2011), pp. 3616–3620. ISSN: 18777058. DOI: 10.1016/j.proeng.2011.08.677. URL: http://dx.doi.org/10.1016/j.proeng.2011.08.677.

[47] WHO. "Healthy workplaces : a model for action." In: *Who* (2010), pp. 1–32. ISSN: 7117181788.

[48] World Health Organization (WHO). "Workers' health: global plan of action." In: *Sixtieth World Health Assembly* May (2007), pp. 1–8. ISSN: 0300-5127. DOI: 10.1042/BST20160047. URL: http://scholar.google.com/scholar?hl=en{\&}btnG=Search{\&}q=intitle:Workers+?+health:+global+plan+of+action{\#}0.

[49] D. P. Wyon and P. Wargocki. "Room Temperature Effects on Office Work." In: *Creating the productive workplace* November 2015 (2005). ISSN: 1098-6596. DOI: 10.1017/CBO9781107415324.004. arXiv: arXiv:1011.1669v3.

[50] L. Yang, H. Yan, and J. C. Lam. "Thermal comfort and building energy consumption implications - A review." In: *Applied Energy* 115 (2014), pp. 164–173. ISSN: 03062619. DOI: 10.1016/j.apenergy.2013.10.062. URL: http://dx.doi.org/10.1016/j.apenergy.2013.10.062.

[51] L. Youseff, M. Butrico, and D. Da Silva. "Toward a Unified Ontology of Cloud Computing." In: *2008 Grid Computing Environments Workshop*. IEEE, 2008, pp. 1–10. ISBN: 978-1-4244-2860-1. DOI: 10.1109/GCE.2008.4738443. URL: http://ieeexplore.ieee.org/document/4738443/.

[52] W. Zeiler, G. Boxem, D. Vissers, and R. Maaijen. "Indoor air quality and thermal comfort strategies: the human-in-the-loop approach." In: 2011.

[53] W. Zeiler, D. Vissers, R. Maaijen, and G. Boxem. "Occupants' behavioural impact on energy consumption: 'human-in-the-loop' comfort process control." In: *Architectural Engineering and Design Management* 10.1-2 (2014), pp. 108–130. ISSN: 1745-2007. DOI: 10.1080/17452007.2013.837252. URL: http://www.tandfonline.com/doi/abs/10.1080/17452007.2013.837252.

[54] G. Zichermann and C. Cunningham. *Gamification By Design: Implementing Game Mechanics in Web and Mobile Apps*. 2011, p. 182. ISBN: 9781449397678. URL: http://medcontent.metapress.com/index/A65RM03P4874243N.pdf.