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Bachelor in Computer Science

Tackling the impact of noise in the productivity of collaborative software development projects located in open spaces

Dissertation submitted in partial fulfillment
of the requirements for the degree of

Master of Science in
Computer Science and Informatics Engineering

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FACULDADE DE
CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

September, 2021

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[1] `https://github.com/joaomlourenco/novathesis` [2] `http://www.di.fct.unl.pt`

ACKNOWLEDGEMENTS

I would like to thank my adviser, Professor Vasco Amaral, my co-advisor, Professor Miguel Goulão, and my colleague João Cambeiro, for all the dedication in helping me improve my work, either by validating my ideas or providing me with new ones. Much of the quality of this work is due to the insight they provided me.

I also would like to thank the NOVA LINCS Research Laboratory for making this research possible by providing all the hardware necessary to its realization and for making their laboratory available for me to test my system.

Last, but not least, I want to thank my family, my girlfriend and my friends with all my heart, for bringing me up when I was down, for celebrating with me when I was up, for always supporting me and for helping me to finish this final step of my Master's degree possible.

Thank you all.

ABSTRACT

In a context of open space office environments, with multiple teams in the same office room working on different projects, a commonly reported issue is the disruptive amount of noise generated by the occupants. High noise levels are mainly attributed to communication necessities both among members of the same team and among members of different teams.

Despite the fact that coexistence rules can be established among occupants, with time, the communication needs and stress levels lead to the disrespect of the agreed rules and the increase of the room's noise level. Frequently a third party needs to be put in place to help enforcing acceptable noise level, *e.g.* a librarian or a teacher. To ensure the best work conditions for all office occupants, as well as keeping their productivity high, the noise level should be as low as possible while still allowing communication.

To control the noise level inside an office, we propose the implementation of a Cyber-Physical System that utilises the Internet of Things technologies to detect the team(s) responsible for producing disruptively-high noise levels. By enriching the office's physical environment with sensors and the use of sound source location techniques, we can identify the workspace(s) from which the noise was generated, and then reach its occupants through the system's actuators. Upon identifying the responsible team, the system communicates with it through a LED lamp, using a colour and intensity code, informing them about their noise level.

The goals of this work are to design and implement a Cyber-Physical System to address the problem of high noise levels in software development office environments, and to study the behaviour of the workers when prompted by the system actuators about their high noise level. Through the usage of functionality tests, we can ensure the functionality of the system and designed simulations and experimental guidelines for enabling future works to measure its efficiency at keeping the overall noise level low and for assess the correlation of its efficiency with its occupants' productivity.

Keywords: Cyber-Physical Systems, Internet of Things, Office Noise Control, Open Space Office

RESUMO

Num contexto de ambientes de escritórios *open space*, com múltiplas equipas a trabalhar em projetos diferentes, um dos problemas reportados regularmente é a quantidade disruptiva de ruído gerada pelos ocupantes. Níveis elevados de ruído são atribuídos principalmente à necessidades de comunicação dentro de uma equipa, ou entre equipas.

Apesar de poderem ser estabelecidas regras de coexistência entre ocupantes, com o tempo, as necessidades de comunicação e os níveis de stress levam ao desrespeito dessas regras e ao aumento do nível de ruído da sala. É frequente o recurso a uma pessoa para ajudar a manter um nível de ruido aceitável. Para assegurar as melhores condições de trabalho, tal como manter os níveis de produtividade altos, o nível de ruído deve ser o mais baixo possível, tendo em conta as necessidades de comunicação entre ocupantes.

Para controlar os níveis de ruido dentro de um escritório, propomos a implementação de um Sistema Ciber Físico que utilize tecnologias *Internet of Things* para detetar o(s) responsável(eis) pela produção dos níveis de ruido disruptivos. Através do enriquecimento do ambiente físico do escritório com sensores e a utilização de técnicas de localização de origem de som, é possível identificar o(s) espaço(s) de trabalho onde o ruido teve origem, e alcançar os utilizadores desse espaço através dos atuadores do sistema. Após identificar a(s) equipa(s) responsável(eis), o sistema comunica com eles através de luzes LED, usando um código de cor e intensidade para os informar sobre o seu elevado nível de ruido.

Os objetivos deste trabalho são o de conceber e implementar um Sistema Ciber Físico que tenta resolver o problema dos altos níveis de ruido num ambiente de escritório de desenvolvimento de software e o de estudar o comportamento dos trabalhadores quando notificados pelo sistema sobre o seu elevado nível de ruido. Garantimos que o nosso sistema funciona como suposto através de testes de funcionalidade e apresentamos simulações e diretrizes experimentais para permitir que futuros trabalhos possam medir da sua eficiência em reduzir os níveis de ruido produzidos e avaliar a correlação entre esta eficiência e a produtividade dos ocupantes.

Palavras-chave: Sistema Ciber Físico, *Internet of Things*, Controlo de Ruído, Escritório *Open Space*

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Acronyms

API	Application Programming Interface.
BAS	Building Automation System.
CPS	Cyber-Physical System.
DOA	Direction Of Arrival.
EMA	Exponential Moving Average.
IoT	Internet of Things.
MA	Moving Average.
MQTT	Message Queuing Telemetry Transport.
SSL	Secure Sockets Layer.

CHAPTER 1

INTRODUCTION

Chapter 1 presents an introduction to this dissertation. Section 1.2 provides insight on the institutional context of our work. Section 1.1 gives some context to the developed work. Section 1.3 explains why this study is worthwhile, presenting its motivating factors. Section 1.4 states the main problem being tackled and the final goals of the study. Section 1.5 presents the dissertation contributions. Section 1.6 gives an overview on the solution proposed and case study. Section 1.7 presents the structure of the document.

1.1 Context and Description

"A software organization's most valuable assets are its engineers"[19]. This statement is true both due to (1) the extra value that a productive individual represents to the organization and to (2) the effort and time costs of training new engineers, which can slow down the organization.

It is in the best interest of every software development organization to understand how the physical work environment impacts their engineers. Such understanding enables them to keep high levels of job satisfaction and productivity among their workers, which in turn can increase significantly the final value of the organization's product, as well as decrease time and costs of production. Low levels of work productivity in office environments can be co-related with many physical variables, external to the office occupant, such as temperature, air quality, lighting and noise level.

From those physical variables, some studies highlight office noise level as one of the most impactful physical variables to the worker's productivity [27], particularly in open office environments, where the noise level is harder to control. We solidified this statement by analyzing data gathered through the questionnaire in Appendix A, scrutinized in chapter 4, as well as by the many pieces of research conducted on this field, explored in detail in Chapter 3.

The term "noise" is defined as sound signals that bear no information with variable intensity; in other words, "unwanted sound" [25]. The control of noise levels presents a real challenge in any office environment, with different scientific fields presenting many approaches to try to overcome it. This challenge is even harder to address in a context of an open space office environment, where the physical barriers that usually block the propagation of sound, *e.g.* walls, are few or non-existent.

Our approach consists of introducing an automatic control system which can be defined as a Cyber-Physical System (CPS), a system that integrates computation with the physical processes. This type of system is already widely used to control other physical variables like temperature and light intensity, to try to control the noise level in an open space office environment. They can be found in various fields of work such as medicine, aeronautics, transportation, cybersecurity, military defence, robotics, industrial production and general smart buildings [38]. The rise of computation and communication functionalities embedded in various types of physical environments created new ways of improving office productivity due to their potential to enhance the users' interactions with the system and the system's functionalities. These enhancements can be accomplished on many different levels, such as automation of tasks for increased efficiency, easier manipulation of physical components through a cyber medium or more detailed monitoring of the physical variables of the environment.

1.2 Institutional Context

Our work was developed in the context of the Automated Software Engineering (ASE) group of NOVA LINCS, which is responsible for works on the development, conception and implementation of Cyber-Physical Systems. They provide us with the financial support to acquire all the equipment necessary to the realization of our work, as well as the physical space in which we tested our system.

1.3 Motivation

By ensuring better overall work conditions, the CPSs can improve the productivity and efficiency of the workers [1]. This idea, coupled with the impact of office productivity on the final product value of a company and the fact that around seventy per cent of the companies have open-space offices in their facilities [23] makes this a subject worthy of research. However, instead of designing a CPS to control all the physical variables of an environment, we chose to design our system around controlling just one physical variable, noise.

The decision to design our CPS around noise reduction is due to it being one of the physical variables with a higher negative impact on office productivity [27]. This statement is particularly true for software engineering companies, where an "above average"percentage of offices are open-space offices due to the communicative nature of most of the work performed at these companies. It is not uncommon for these companies to have different teams in the same open space office, either working on the same project or in different ones, thus needing to be in communication with each other.

Furthermore, unlike room temperature or light intensity, which can be easily manipulated by changing the settings of the air conditioning system or the light intensity of the lamps, noise is a hard physical variable to control. Most of the noise in an office environment is produced by the humans occupying it, either directly or indirectly. This implies that the CPS 's actions must try to convince the office occupants to suppress their noise-producing behaviours. However, if these actions are too intrusive, they can also harm the productivity levels of the engineers, going against the main goal of the system: improving productivity.

Noise is one of the most challenging physical variables to control and manipulate, which serves as an extra challenge and motivation to the realization of this dissertation.

1.4 Problem Statement and Final Goals

The main goal of our work is to design, implement and deploy a CPS responsible for controlling the noise level in a multi-team software development open space office environment. A system with the ability to detect and locate high noise level sound signals inside an office room, and notify the human entity responsible for its creation, stepping towards a human-in-the-loop solution and driving the human to reduce his production of noise and contribute to the increase of productivity for all occupants of the office room.

This system is as a tool to identify and notify office occupants responsible for high noise level production and serves as a platform to future experiments on (1) how much does the system improve the office occupants' productivity, (2) how effective is the designed CPS in accomplishing its goals of controlling the noise levels and (3) how the human participants of the system would adapt to its actions. In this dissertation, we also aim at providing all the necessary guidelines for the preparation and execution of these experiments, as well as on how to correctly interpret the data gathered during their execution, using simulation techniques to display such guidelines.

This dissertation incorporates the design of the mentioned CPS, functionality tests to the system and research experiment guidelines, accompanied by possible simulated scenarios, to evaluate how a software development open office environment equipped with our CPS designed to monitor and control the noise level can impact the occupants' productivity.

1.5 Contributions

This dissertation contributes with the design, implementation and deployment guidelines of a CPS at Faculdade de Ciências e Tecnologia from the Universidade Nova de Lisboa's facilities, emulating a software development open space office environment with multiple teams. Besides its core functionalities, described in the previous section of this document, the implemented system will contribute to future works on the context of physical variables manipulation to achieve productivity improvements by providing a stable starting point for such studies.

This dissertation will also contribute with guidelines to execute an experiment to understand how the system impacts the productivity of the occupants of the office environment, supported by simulated scenarios to exemplify the data analysis future works should approach.

Furthermore, we contribute with the analysis of the questionnaire in Appendix A on how the students attending a course of Computer Science at Faculdade de Ciências e Tecnologia that emulates the open space office environment of a software development organization feel, regarding the physical variables of their work environment (*e.g* light intensity, noise, temperature) and how it affects them.

1.6 Solution Overview

The experiment to which we provide guidelines in this dissertation consists in a research project to be developed in the classrooms of the course "Actividade Prática de Desenvolvimento Curricular - Projecto " [1] at Faculdade de Ciências e Tecnologia from Universidade Nova de Lisboa. In this course, groups of five students finishing their bachelor's degree in Computer Science will be provided with a multi-team open space office environment, where they must develop a project during a whole semester, emulating the environment of an open space software engineering office.

This research project consists of deploying our noise controlling CPS in the two classrooms available for the APDC course. One room will have all the functionalities of the system available and will be denominated smartOffice, and the other room will only have the data gathering functionalities, representing the environment of a standard office room and the control data for the experiment.

Figure 1.1 presents a simplistic abstraction of the goals of the experiment and the methodology to achieve them. The system would gather data on noise levels, identify and notify the group(s) responsible for high noise level's production and monitor their reactions. The data gathered from this whole process will then allow the researchers to make conclusions on two different levels. On a smartOffice room level, we can assess the effectiveness of the CPS by observing the impact of the system's actions on the overall noise level, taking into consideration the evolution of noise level over time, gathered by

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[1] Practical Activity of Curriculum Development - Project

the different noise level sensors and the results of a series of questionnaires in which the students should participate. On the other hand, and at a higher level, we would compare the evolution of noise level on both rooms, the smartOffice and the control room, showing the advantages or disadvantages of a room enriched with our CPS trying to reduce the noise level when compared to a room without one.

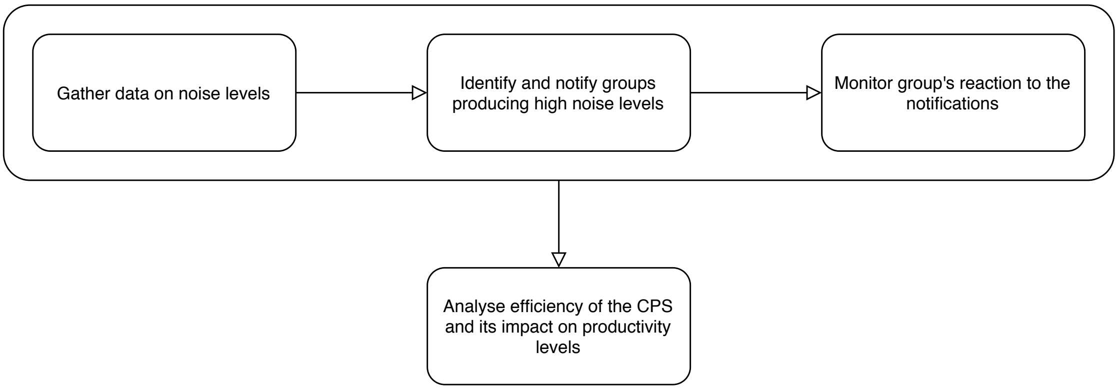

Figure 1.1: Overview of the case study

This realization of this experiment can provide insight on how our CPS, designed to reduce office noise levels, can impact the productivity levels of the working teams and the value of their final products on a software development open space office environment, with each group of students representing a team of engineers in a big software company.

1.7 Document Structure

The remainder of this document is organised as follows:

- **Chapter** 2 provides the necessary background on CPS, Direction Of Arrival (DOA), Internet of Things (IoT) and Exponential Moving Average (EMA), key concepts fundamental in understanding this dissertation.
- **Chapter** 3 contains an overview on related work and the state of the art for this dissertation.
- **Chapter** 4 analyses the empirical data used to identify the problem of noise levels in working environments.
- **Chapter** 5 provides a detailed overview on the implemented CPS and its components and functionalities.
- **Chapter** 6 consists of the analysis of the integrity test results.
- **Chapter** 7 contains the guidelines for the preparation, execution and analysis of the experiment, including simulated scenarios.

- **Chapter** 8 addresses some diverging subjects regarding the limitations of the context of this dissertation and the validity of its conclusions.

- **Chapter** 9 presents the conclusion of our dissertation.

Chapter 2

Background

This chapter explains in detail the critical concepts for the understanding of this dissertation. Design Science Research in section 2.1, Cyber-Physical System in section 2.2, Internet of Things in section 2.3, Direction of Arrival of sound signals in section 2.4 and Exponential Moving Average in section 2.5.

2.1 Design Science Research

In their work on Design Science Research in Information Systems, Vijay Vaishnavi *et al.* present two key definitions: *Research* as "the activity that contributes to the understanding of a phenomenon", and *Design* as "to invent and bring into being" [46]. Design Science Research can be defined as the research that provides the necessary understanding to design and create something.

Following the work of Vijay Vaishnavi *et al.*, a typical Design Science Research process can be split into 5 steps, each with its own output:

- **Awareness of the Problem** - The process of becoming aware of a topic worthy of research. The output of this phase is a formal or informal Proposal for a new research.

- **Suggestion** - This creative step is intimately related with the Proposal outputted by the Awareness of the Problem phase and consists of conceptualizing a new functionality using new or existing elements, as a way to complement the Proposal with a Tentative Design (the output of this phase).

- **Development** - The development and implementation of the Tentative Design phase, outputting an Artifact. The focus main focus of this step should be on the design of the Artifact and not so much on its implementation.

- **Evaluation** - After the Development phase, this phase sees the Artifact evaluated following the criteria implicitly contained in the Proposal. The result of this is the Performance Measures.

- **Conclusion** - The final phase of the Design Science Research cycle is to draw conclusions from the Performance Measures. It outputs the final Results of the cycle.

As shown in Figure 2.1, taken from the same author, the phases of Development, Evaluation and Conclusion can close a Design Science Research cycle by achieving Knowledge Contribution. This can happen by the occurrence of a Circumscription during the Development or Evaluation phases, or due to the natural end of the cycle through the Conclusion phase. In all cases, the Knowledge Contribution achieved at the end of the cycle can be satisfactory, thus ending the Design Science Research Process, or can start a new cycle by making the researchers aware of new problems.

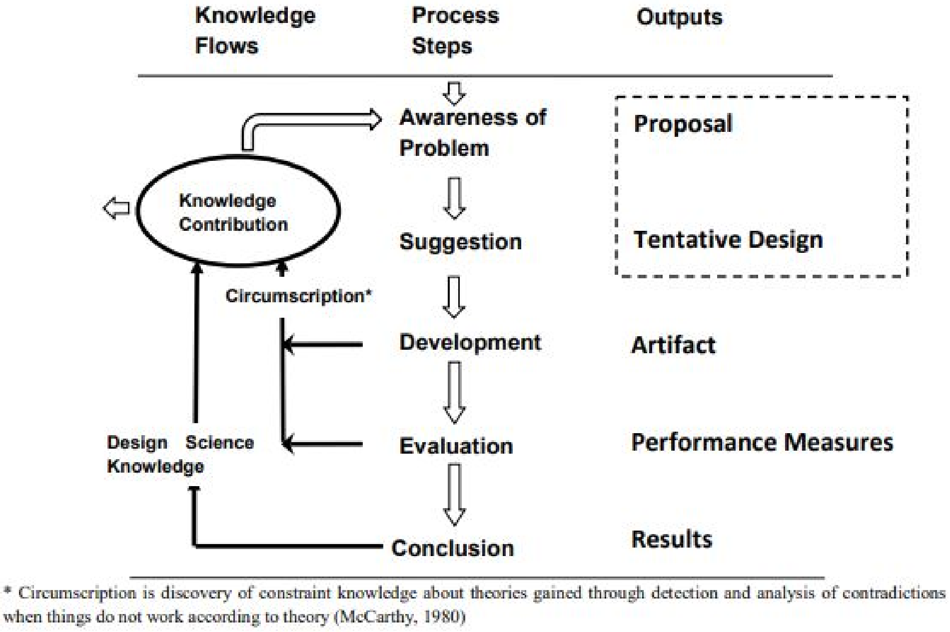

Figure 2.1: "Design Science Research Process Model (DSR cyle)", from the work of Vijay Vaishnavi *et al.* [46]

The Design Science Research Process was applied to our work when trying to conceptualize a solution for the noise problem in multi-team open space office environments.

2.2 Cyber-Physical Systems

A system composed of both physical and cyber components and network mechanisms, engineered to support the integration of computation with physical processes is called a CPS [28]. This integration enables new ways of interacting with the system through the expansion of the capabilities and functionalities of the physical components, being considered by some as "the next computing revolution" due to the impact it can have in our lives [30, 38]. We can find CPSs in various fields of work: medicine, aeronautics, transportation, cybersecurity, military defence, robotics, industrial production, smart buildings and more [38]. Although each field needs a CPS with its specific properties, we can identify some vital architectural layers in all of them.

- **Physical Plant -** Composed by the parts of the system that do not incorporate electronic or digital components, which can be mechanical components, humans or physical, biological or chemical processes.
- **Interface Layer -** Made by the sensors and the actuators of the system, this layer is responsible for gathering the data from the Physical Plant and for performing the tasks received from the control layer, representing the interface between the Physical Plant and the Control Layer.
- **Control Layer -** Consists of computational platforms that receive and analyse the data from the Interface Layer. Based on the analysis results, the Control layer makes a decision and notifies the actuators to perform a specific task in response.
- **Network Fabric -** Enables the communication between all the CPS components through network mechanisms.

The design and implementation of CPSs require knowledge of various technologies [38]. CPSs make use of mechanisms where the physical processes affect computations that in turn, affect physical processes. This technique is called a feedback loop [29] (Figure 2.2). The system must contain both sensors that provide data to the cyber components and actuators that interact with the physical components in some way. The cyber components of the system decide how to react correctly to the gathered data. As an example, the sensors can detect that a room is empty, and send that data to the cyber components which in turn, after being sure that the room is empty, send a signal to an actuator that turns the lights off.

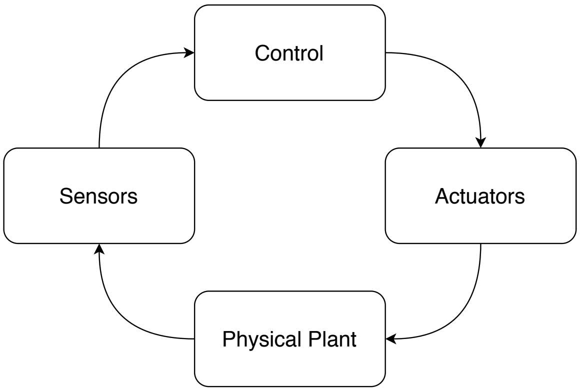

Figure 2.2: Feedback Loop of a CPS

In the context of a software development office environment, engineers usually design the CPSs with Building Automation in mind. A Building Automation System (BAS) is a type of CPS usually in charge of monitoring and controlling physical variables of a building such as room temperature, light intensity and power consumption. The CPS optimises the workspace environment, providing the occupants with better work conditions while also, in most cases, reducing the power consumption of the office [40]. The degree of optimisation is highly dependent on the system's design and implementation since there is a wide variety of options in components, software, platforms and methods. The real challenge is to utilise all that heterogeneity efficiently to create a CPS most suited for the specific needs of each project.

2.3 Internet of Things

The IoT is a key enabler of the CPS's functionalities. Due to the efforts made in diminishing electronics' size and cost, it is now possible to enhance objects of the physical world with small computational components [24]. With these computational enhancements, objects can be connected to the Internet and become *smart objects*. By using technologies such as Bluetooth, Wi-Fi and telephonic data service, the *smart objects* allow for new ways of data gathering from their surrounding environment [14].

The interconnectivity created between *things* through the Internet allows the control of these objects through a remote control platform (IoT Platform). Since almost everything can be turned into a smart object, these platforms are essential in helping the systems to cope with the high heterogeneity of hardware and data. The platforms create an abstraction of all the *things* and work as a medium between them and the system's main server. When the main server wants to communicate with a *thing*, it sends the request to the IoT Platform, which then handles the necessary protocols to establish communication with the physical object. This allows the simplification of the main server logic since all the communication logic is placed in the IoT Platform.

The applications for IoT technologies seem only limited by human imagination. These can go from simplifying everyday life processes, *e.g.* a coffee machine that automatically turns on when the user wakes up, which is detected by a sensor, to more critical ones like facilitating complex medical diagnoses or allow the use of more complex military defence systems.

2.4 Direction Of Arrival

DOA algorithms make use of an array of microphones to estimate the direction of arrival of a sound signal. There are various ways to estimate the DOA of a signal. The most commonly used methods consist of calculating the time differential of the arrival of a sound signal to each microphone. With this data, the algorithms can estimate the direction and distance of a sound signal source.

This type of algorithms are now present in most of the voice-enabled technologies, such as Smart Home Hubs like the Google Home Assistant or the Amazon Virtual Assistant, which utilise DOA algorithms to estimate the direction of the voice command. Knowing the location of the source of the voice command enables the cancellation of noise, by ignoring signals coming from all the other directions, and isolating the voice command coming from the estimated direction.

In this dissertation's context, the DOA algorithm will also serve the purpose of locating the source of sound signals. Since both the room's dimensions and the teams' workspace location are static, we can abstract the room to a two-dimensional world with multiple areas, each owned by a software engineering team. This abstraction enhances the performance of the algorithm, which can output the sound source location as one of the predefined areas instead of coordinates.

2.5 Exponential Moving Average

Exponential Moving Average (EMA) is a type of Moving Average (MA) [17, 18]. A MA is a computation of the average over time that enables the smoothing of abrupt increase or decrease of new values by preserving information of older values. All types of MA are extensively applied in data analysis, especially in the field of Technical Analysis, where it is used to smooth the fluctuations in stock prices by taking into account price histories[17].

The SMA is the arithmetic mean calculation of all values $(A_1, A_2, ..., A_n)$ over n time periods:

$$SMA = \frac{A_1 + A_2 + ... + A_n}{n}$$

In this method, all values have the same weight in the mean calculation. This makes SMA less responsive to changes in the newer values, the larger amount of time periods we are considering, *i.e.* if we have a lot of low values, it will take more than a few high values to provoke a significant increase of the SMA value.

The EMA takes the same idea of the SMA, but attributes weight to every value, with more recent values having more weight on the mean calculation[16, 17]. This difference highly increases the responsiveness of the mean value to newer, more dissonant, recorded values, while still not ignoring the older ones. To calculate the EMA at a given time (EMA_n), we add the previously computed mean (EMA_{n-1}) and the new value (A_n) after multiplying both of them by their respective weight determined by the α value, which can be changed according to the goals of the analysis (usually, the more time periods we take in account, the lower the value attributed to α):

$$EMA_n = (A_n \times (\frac{\alpha}{n+1})) + EMA_{n-1} \times (1 - (\frac{\alpha}{n+1}))$$

Figure 2.3: Difference between EMA (orange) and SMA (blue)[1]

In the context of this dissertation, we will be using EMA techniques to be able to "ignore" non-significant noise spikes like a sneeze or some object falling to the ground. Although the noise produced by this type of events should not be ignored, what we are trying to capture is a continuous production of noise and not occasional noise spikes. In other words, we will be looking for EMA values above a certain threshold and not just noise level values.

The choice of EMA techniques over SMA ones is due to the difference of responsiveness to new values between them. Although we want older values to have importance still, we wish to minimise the time it takes for the mean values to go up when a group suddenly starts producing high levels of noise. If we used the SMA technique, most of the time the students would naturally lower the noise level before the system even detected there was noise being produced. More details on the use of EMA to detect high noise levels are provided in chapter 5.

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[1] Computed with data from `https://www.tradingview.com`

CHAPTER 3

STATE OF THE ART

This chapter presents the state of the art for this dissertation. In section 3.1, we present studies made on the correlation between job satisfaction and productivity. Section 3.2 presents various approaches to measure a software engineer's productivity. Section 3.3 presents some applications of CPSs in various fields of work. Section 3.4 explains the decision of using WSO2 IoT Server. Section 3.5 presents the discussion on the validity of experiments done in an academic context for a business environment. Section 3.6 contains the current European and American regulations for noise levels in a work environment.

3.1 On job satisfaction and productivity

The understanding of software engineers' work methodologies and the influence of physical environments has on them is critical to optimise their productivity. It is undeniable that the physical environment surrounding the software engineers has an impact on their productivity[27], but to what extent is it still a topic worthy of research. The big challenge is to find an environment that equally satisfies a collective of engineers' needs since each one has his own. An excellent example of this is the debate of open-space offices vs individual cubicles[35].

Research made by Johnson *et al.* [19] shows an empirical study on how the work environments at Microsoft impacts both the satisfaction and perceived productivity of their software engineers. While job satisfaction describes the feelings of the engineers towards his job and workplace, perceived productivity quantifies the amount of work done by the engineer when compared to the amount of work he had predicted he would do. The study consisted of surveys and interviews with 1159 Microsoft employees on many aspects of their work environment such as personalisation, social norms, room composition, atmosphere, furniture and productivity strategies. Their conclusion points out in two different directions. The possibility of working privately and without interruptions translates into improved perceived productivity, but so does the ease of communication between engineers. Quoting one of the interviewed workers, "the pro is having everyone in the same room, but the con is also having everyone in the same room". While on the open-space side, we have improved team communication and interaction; on the other, we have an almost noise-free environment without recurrent distractions.

These results emphasise the need to find common ground between the two approaches. Large companies, with significant financial power, can include private spaces in their open-space offices, which can have a positive impact on the overall productivity of the employees. This approach provides the engineers with a communication-rich environment to work on, while still allowing them to isolate themselves from the team and work in a private noise-free environment.

Storey *et al.* [43] deepened this research by presenting a theory on the correlation between job satisfaction and perceived productivity in a Software Engineering context. The authors took the seminal work of Judge *et al.* [21] as a starting point, which identifies a bi-directional relationship between both those concepts, influenced by seventeen distinct factors found in many fields of work. Storey *et al.* [43] narrowed down these factors to the ones found in a software development environment (*e.g. high work complexity*) and proved the same bi-directional relationship theorised by Judge *et al.* [21] applies to a Software engineering work environment.

3.2 Measuring productivity

The best way of measuring the productivity of software engineers is still a matter of debate. Despite each approach using different metrics to calculate productivity, it is possible to identify three basic elements common to approaches: inputs, outputs and efficiency. [34] The approaches most commonly adopted to analyse software engineers' productivity consist in calculating their efficiency through the amount of code produced (output) over a time period (input) [48][20][8]. However, some studies highlight the need for other ways of measuring productivity, since a typical day of work of a software engineer consists of more than just producing code [33]. Attending meetings, reading and writing emails and code documentation, performing code debugs and general unplanned work are some of the tasks identified by Fritz *et al.* as unproductive activities when studying software engineers' perception of productivity.[34]

Many companies started using perceived productivity as a better method of measuring the productivity of their employees. Instead of the previously discussed methods, perceived productivity captures the way the engineer perceives his productivity during a period of time. This data is usually gathered through questionnaires [19]. The significant advantage of using perceived productivity is that it accounts for factors like the type of tasks performed or the skill set of the engineer.

Since we know that perceived productivity has a strong correlation to actual productivity [13], both types of analysis are viable, depending on the context. For measuring the productivity of a specific task or work process, the more strict approaches output a more credible value of productivity. On the other hand, for measuring the productivity over a group of tasks with different natures, assessing the perceived productivity might output a value closer to the truth. As an example, let us consider a 3-hour office meeting. There is no better way to know if the meeting was productive apart from asking the meeting participants about it since, during that time, none of the participants was writing lines of code.

3.3 On Cyber-Physical Systems usage

As mentioned previously, the applications of CPSs extend themselves to many fields of work.

Khaitan *et al.* published a survey in 2015 review over one hundred different researches on the design and applications of CPSs, categorising them into eighteen different fields of work [22].

Gunes *et al.* also surveyed over one hundred distinct CPSs, while taking into consideration eight different domains: Smart Manufacturing, Emergency Response, Air Transportation, Critical Infrastructure, Health Care and Medicine, Intelligent Transportation, Robotics and Building Automation. [15].

A critical point referenced in both the presented works [15, 22] is that advances made in the development of CPSs are tightly related to the research advances made with cutting-edge technologies. Each new technology created or upgraded creates room for improvement on CPSs and the possibility of application to new domains.

Both pieces of research also reference the main challenges of designing CPSs, which vary depending on the application we have in mind when designing the system. Gunes *et al.* identify six categories of challenges: Interoperability, Security, Dependability, Sustainability, Reliability and Predictability.

3.4 IoT Platforms

Since our work takes the previously developed work at the NOVALINCS' research project named "SmartLab" [4, 36, 40] as a starting point for implementing our CPS, we will adopt the WSO2 IoT Server as the IoT platform for our CPS. Nonetheless, the analysis of the different options is worth mentioning.

In his master's thesis [40], Pedro Simão presents detailed analysis on architectures, key concepts, data analytics, communication models and general features of five IoT Platforms: WSO2 IoT, IBM Watson IoT, ThingSpeak IoT, Microsoft Azure IoT and Amazon

Web Service. João Cambeiro also performed analysis on the IoT Platforms of WSO2 Azure and IBM in his master's thesis [4], although more superficial. Both the mention works refer that each IoT Platform has its advantages over the others, and the choice needs to be based on the context of the system we want to implement. That being said, the WSO2 IoT Server was the choice to implement the SmartLab system, and will be the IoT Platform for our system as well since the context of both projects is the same.

3.5 On the validity of Academic experiments in a business context

The behaviour and work methodologies of a student are not the same as a professional worker. We can notice these differences in all fields of work. They are the root of some arguments defending that the conclusions taken from experiments with students are not valid in an industrial context. The work of Per Runeson [39] came to conclude that, in a Software Engineering context, there is no data to support either opinion. His experiment consisted of comparing data from freshman students, graduate students and workers when performing a series of tasks. Although freshmen students showed significantly less performance when compared to the other two groups, he concluded that he "can neither reject nor accept the hypothesis on differences between freshmen, graduate students and industry people" since the data supported none of the theories.

Carver *et al* present a crucial work on this subject[5]. In it, the authors explore the different pros and cons of using students as subjects in empirical studies in software engineering. In one section of the document, they approach the subject of external validity of the conclusions taken from such empirical studies. While they could not provide an answer to the problem, they list some favourable arguments in favour of the external validity of these studies.

We can not assume the complete external validity of the conclusions extracted from empirical studies that use students as subjects. However, we can also not assume that they have no external validity at all. Besides, using students instead of workers as the subject is also in the interest of the industrial companies. By avoiding the involvement of their workers in these studies, they prevent the existence of extra tasks during work time, which can have an impact on their productivity towards the company[5].

We will assume that the conclusions have partial external validity, requiring the context of the workers and the students to be equivalent. For these reasons, they can not be blindly applied to any industrial context.

In this dissertation, we designed the CPS for an office environment, and the guidelines for the experiment suggest an academic environment that tries to mirror the industrial office one. With that in mind, we estimate that the conclusions of the experiment would present some level of external validity for a context of industrial open-space software engineering office environments.

3.6 Workplace regulations regarding noise levels

We come to expect some degree of noise in office environments, but continued exposure to excessive noise levels at the workplace can not only disrupt the productivity of the occupant but also harm their mental and physical health [3]. Among the effects are: stress, anxiety, headaches, elevated blood pressure, fatigue, irritability, digestive disorders, increased susceptibility to colds and other minor infections and instant or gradual loss of hearing [7].

In order to prevent people from working under these noisy conditions, governments around the world have published legislation that limits the noise levels dimmed acceptable to have in a workplace. In 2003, the Directive 2003/10/CE was accepted by the European Parliament, regarding safety and health in the context of exposure to physical variables in the workplace, namely noise. The Directive states that "the risks resulting of noise exposure should be eliminated at the source and reduced to a minimum", establishing the maximum threshold for noise level at 87 dB [44]. In 2006, this Directive was accepted by all the Member States of the EU, including Portugal, thus replacing the national legislations for it.

In the United States of America, Occupational Safety and Health Administration (OSHA) has also publish a Standard, in which they establish the legal maximum average noise level for an 8 hour day of work to be 90 dB [9, 26].

CHAPTER 4

CASE STUDY

This chapter presents a detailed description of the case study of our work and possible future works using our concept. Section 4.1 presents analysis of data gathered through a questionnaire and the reasons for this study to be focused on noise reduction. Section 4.2 consists of a summary of the questionnaire analysis.

The case study for this dissertation consists of a research project brought forth to the classrooms of the course "Actividade Prática de Desenvolvimento Curricular - Projecto" [1] at Faculdade de Ciências e Tecnologia from Universidade Nova de Lisboa. In this course, groups of five students finishing their bachelor's degrees in Computer Science will develop a project on a full-stack scope in a multi-team open office environment, provided by the University. They must develop the project during the whole semester, emulating the environment of a software engineering office.

4.1 Problem Identification

The first step of our work was to assess the extent to witch the high noise levels were, in fact, a problem worth addressing. We presented a questionnaire to 38 students that finished the case study's course. The participants were not evenly distributed by the two rooms so, when relevant, we will distinguish the different rooms to perform reliable analyses.

When asked to choose the physical feature that they considered the most important in making a workplace pleasant for you to work, the majority answered that a noise-free environment was more important than all the other features presented (Figure 4.1).

With this premise, we could already state that many students consider a noise-free environment to be beneficial for their work. However, we still needed to identify if it

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[1] Practical Activity of Curriculum Development - Project

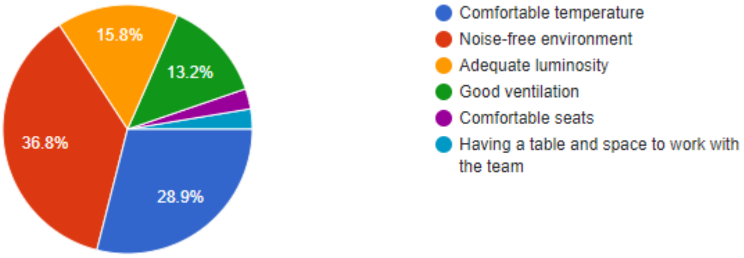

Figure 4.1: Questionnaire answers to "Choose the physical feature that you consider the most important in making a workplace pleasant for you to work."

was a problem in our case study's course. The students were asked about the degree of satisfaction with the different physical features during their semester (Figure 4.2). From their answers, we retrieved a dissatisfaction factor, which identified "Noise-level"as the principal origin of dissatisfaction from the students.

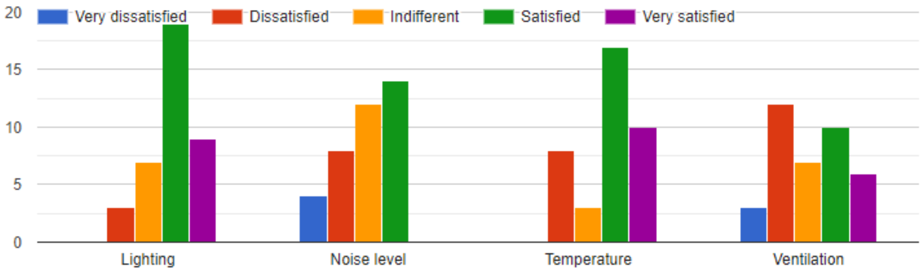

Figure 4.2: Questionnaire answers to "How satisfied are you with the following aspects of your assigned workspace?"

When asked about the regularity of disturbance in their work caused by high noise levels, half the students revealed that it happened "Sometimes"or more, with only 10% of them considering the noise level was never work-disruptive (Figure 4.3).

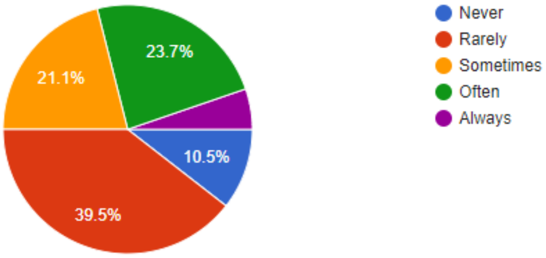

Figure 4.3: Questionnaire answers to "How often did the noise level become too high to keep the concentration in your work?"

To enforce this result, more than 60% of the students also considered that a system that would control the noise level through personal notification of the person making the noise would be beneficial to the overall work environment of the room (Figure 4.4).

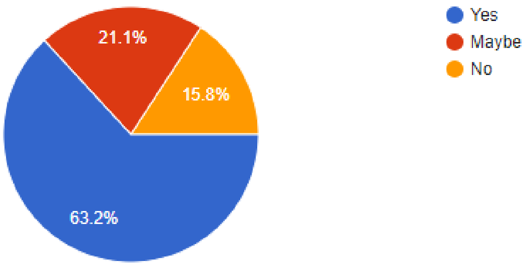

Figure 4.4: Questionnaire answers to "Do you think that a system where the noise level of each worker/group is measured and people get notified that they are being too noisy would be beneficial for the work environment and improve work efficiency?"

The questionnaire also contained some questions about work planning and project management, which identified the main tasks the students felt trouble doing correctly. When asked about the importance of implementing a CPS that would enhance different aspects of their work environment, both "Project Planning" and "Schedule Management" were considered of the most importance, followed by a Noise-level control mechanism (Figure 4.5). Since this dissertation will only focus on the control of the noise level, it will not cover these two mechanisms. Nevertheless, these results are still worth mentioning in the context of this questionnaire.

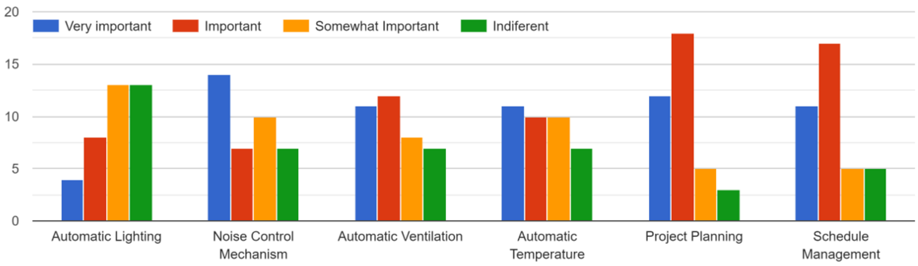

Figure 4.5: Questionnaire answers to "How would you classify the importance of implementing the following Cyber-Physical features for improving the planning and development of projects in APDC's rooms?"

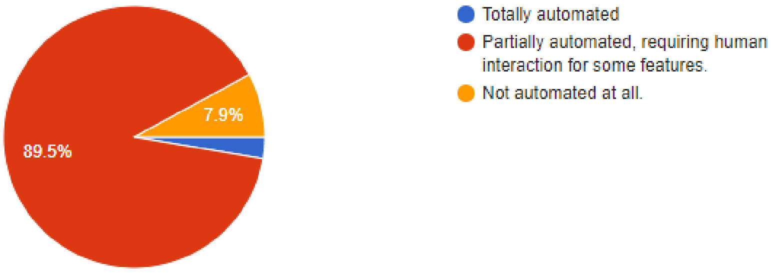

Figure 4.6: Questionnaire answers to "Would you prefer a totally automated Smart Room system, or one that requires some human interaction to function, but in return gives a more personalised experience?"

In the final section of the questionnaire, the students answered questions about the degree of automation they would see fit for a CPS installed in the course's context, to what the majority responded a partially automated system, which required human interaction to perform some operations (Figure 4.6). These answers reveal the importance of considering the inclusion of Human-in-the-Loop mechanisms in the CPS.

4.2 Summary

Summarizing the previous section, we were able to gather the following information from the questionnaire answers:

- 36.8% of the students considered "Noise-free" to be the most important physical feature of a good work environment.
- Noise level is the physical variable that cause higher levels of dissatisfaction for the students.
- 50% of the students considered that "Sometimes" or more, the noise level inside the room became disruptive of their productivity.
- 63% of the students think that a system with the same goals of our CPS would be beneficial for their productivity.
- 89.5% of the students prefer a partially automated system, requiring some degree of human interaction.

These information allowed us not only identify that the noise level in the open space office environment, in which the students had worked, was a problem worth addressing, but also to gathered some information from the students on the proposed solution to reducing the noise level inside the rooms regarding the degree of automation.

Chapter 5

SYSTEM OVERVIEW

This chapter presents a detailed description of the implemented CPS. Section 5.1 provides a general description of the system. Section 5.2 explains the role of the Physical Plant component. Section 5.3 describes the role of the Sensor components. Section 5.4 describes the role of the Actuator components. Section 5.5 describes the Control components and explains the the control mechanisms. Section 5.6 provides the description of the deployment of the CPS.

5.1 Description

This dissertation presents the design and implementation of a CPS enabled through IoT mechanisms that aims at controlling the noise levels inside an office room with different work teams.

The system registers the noise level inside an office room and identifies the human entity responsible for the generation of high levels of noise. After identifying the responsible, the system notifies him about his noisy behaviour through a colour code.

As explained in Section 2.2, these types of systems can be explained under a four-layer architecture, embedded in a Feedback Loop. Figure 5.1 shows the implemented system's feedback loop, with the identification of its different components.

The physical plant is composed of the human occupants of the office room and other noise-producing entities. It is responsible for producing raw data, by generating sound signals, and is affected by the actions of the actuators.

The noise level sensors, the DOA sensors and the card readers compose the Sensors component of the system. These sensors are responsible for gathering the different types of raw data from the Physical Plant and send it to the Control component.

The Control layer consists of Agents, the WSO2 IoT Server, the Noise Control Server

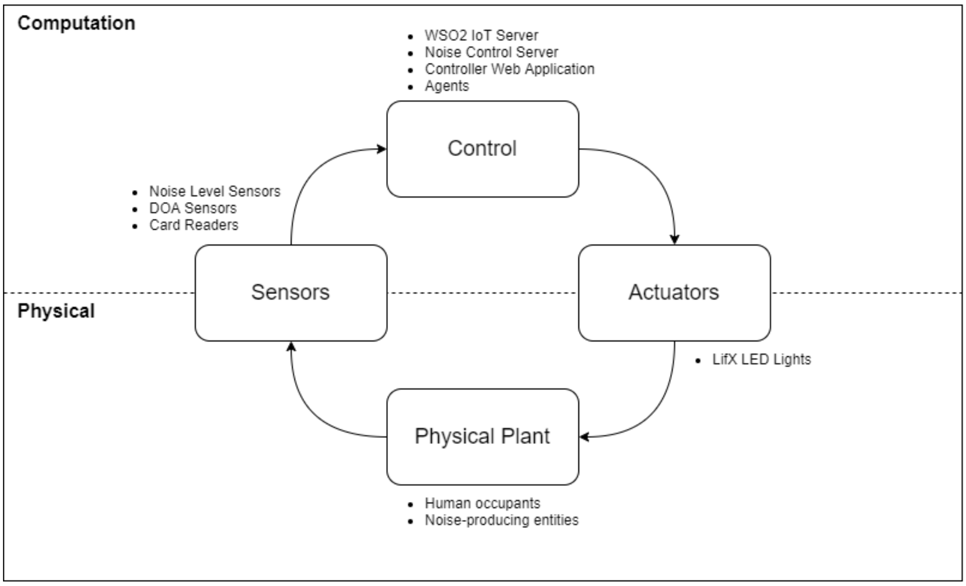

Figure 5.1: Feedback Loop of the implemented CPS

and the Controller Web Application. It is responsible for (1) handling the data provided by the Sensors component, (2) deciding what action best suits the received data and (3) propagate its decision to the Actuators component.

The Lifx LED Lights compose the Actuators component of the system. They are accounted for interpreting the decision received from the Control component and applying the right action, which will impact the Physical Plant of the system.

5.2 Physical Plant

As mention previously, the physical plant of our CPS consists of the occupants of the office room and other noise-producing entities. These entities are mostly personal devices owned by the room occupants, such as cellphones or computers, which can be a source of significant amounts of noise if they are not in silence mode.

Noise is not exclusively produced by humans but also from these devices. The same can be said for reducing the noise levels. It can be achieved by directly reducing the noise produced by the room occupants, but also by the respective owned devices.

Although in practice we could consider the room occupants as noise-producing entities as well, which they are, there is a significant conceptual difference between them. Humans are responsible for their self-produced noise, but also for the noise-producing entities they own. This means that the sensors will gather data from all sound signals, but the actuators will notify only the human occupants of the room, who then must reduce the noise levels of their devices if needed.

In summary, both room occupants and noise-producing devices are producers of raw data by generating sound signals. However, the room occupants are the ones directly affected by the actions of the actuators. The non-human noise-producing entities are indirectly impacted by such actions, through the intervention of the human occupants.

Some exceptions to take into account in the context of our study are noises produced by devices such as an air conditioning system, which have no human to account for, or noises coming from outside the room. Although these noise sources can also jeopardize productivity, they are outside of the scope of our study, since there is no way to attribute responsibility of these noises to one occupant of the office room.

5.3 Sensors

The implemented CPS is equipped with three different types of sensor, each tasked with gathering a specific type of raw data from the Physical Plant:

- **Noise Level sensor** - A sensor for precise measurement of the sound level.
- **Noise DOA sensor** - A sensor that gathers the DOA of sound signals, relative to its position.
- **Card Reader** - A sensor that registers the room's income and outcome of students.

5.3.1 Noise Level Sensors

The Noise Level Sensor chosen to implement in the system was the GM1356 Digital USB Noise Meter (Figure 5.2). This high-precision noise level sensor has a USB port output which enables the handling of the gathered data in real-time. It allows for precise readings of sound signals' intensities while helping the system to keep its responsiveness by providing a raw data stream.

Figure 5.2: GM1356 Digital USB Noise Meter[1]

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[1] Figure from `http://en.benetechco.com/en/products/sound-level-meter-gm1356.html`

5.3.2 DOA Sensors

The DOA Sensor used was the ReSpeaker's 4-Mic Arrays (Figure 5.3), which comes with a DOA functionality already embedded. Just like the Noise Level Sensors, the ReSpeaker 4-Mic Array has a USB port that enables access to the data in real-time.

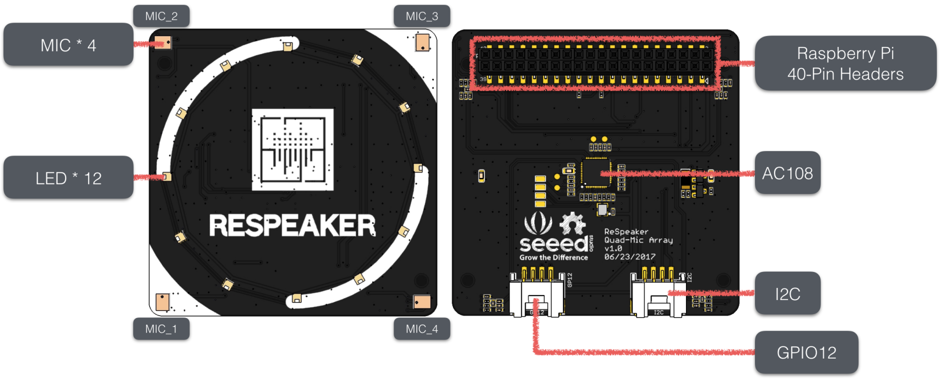

Figure 5.3: ReSpeaker 4-Mic Array[2]

5.3.3 Card Readers

The Card Readers were provided by Faculdade de Ciências e Tecnologia from the Universidade Nova de Lisboa and were used by Pedro Maroco in his master's thesis (Figure 5.4) [31]. The card reader reads the CardID of the student cards' NFC chip, which will allow us to gather data on the occupancy rate of the rooms.

Figure 5.4: Card Reader used by Pedro Maroco in his master thesis [31]

5.4 Actuators

The actuators of the implemented CPS consist of LED lights, to display a colour code. The code indicates to the humans in the Physical Plant the need (or not) of changing their noise-producing behaviour.

5.4.1 LED Lights

The LED lights used to notify the students of their noise level were the Lifx LED Lights (Figure 5.5), which can be controlled by Wi-Fi and can display different colours and levels

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[2] Figure from http://wiki.seeedstudio.com/ReSpeaker_4_Mic_Array_for_Raspberry_Pi/

of intensity. This way, it is possible to display the colour code that symbolises our three levels of noise: (1) light turned off, (2) orange colour and medium intensity, and (3) red colour and high intensity.

Figure 5.5: Lifx Lights[3]

5.5 Control

In this section, we explain the way the different components of the system interact with each other and how the components responsible for controlling the system ensure these interactions. Figure 5.6 shows the component diagram of the implemented system, with all the main components and their interfaces identified.

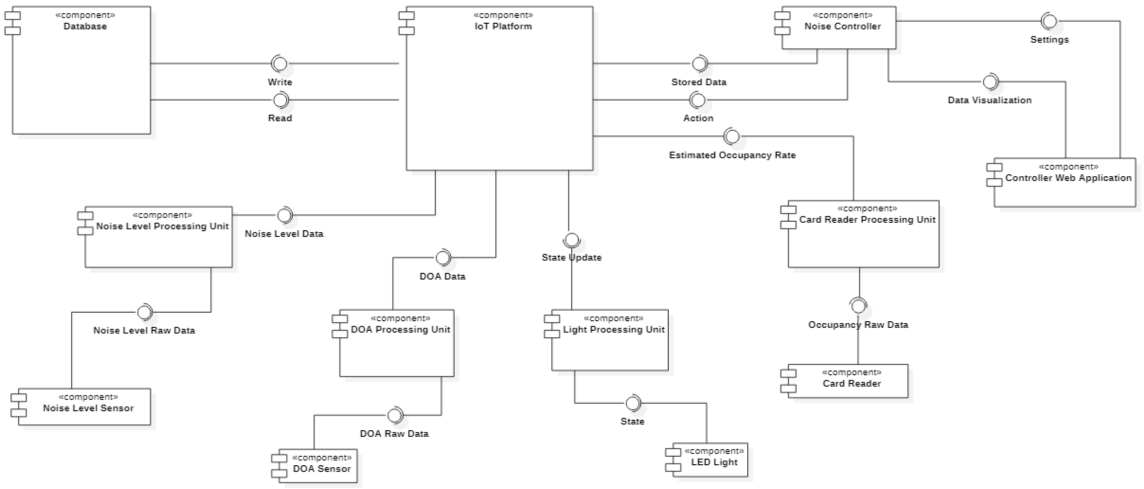

Figure 5.6: Component diagram of the CPS

The components with control responsibilities in our system are the IoT Platform, the Noise Controller and the four types of Processing Unit. Noise Level Sensor, DOA Sensor, LED Light and Card Reader are physical devices that either gather raw data from the

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[3] Figure from `https://eu.lifx.com/collections/lamps-and-pendants/products/lifx`

environment or apply the actions of the system. The Database component ensures the preservation of the data.

The process of gathering noise level data and storing it in the Database of the system is ensured by the Noise Level Processing Unit and the IoT Platform. This process is described by the sequence diagram in Figure 5.7. Since the system starts to operate until it stops, the Noise Level Processing Unit is performing a loop with multiple steps. The loop starts with the Noise Level Processing Unit calling for a new value from the Noise Sensor. The Noise Sensor replies with raw noise level data. The Noise Level Processing Unit computes the EMA which, as explained in Section 2.5, smooths the gathered values and sends the processed data to the IoT Platform. The IoT Platform handles the storing of the data in the database component.

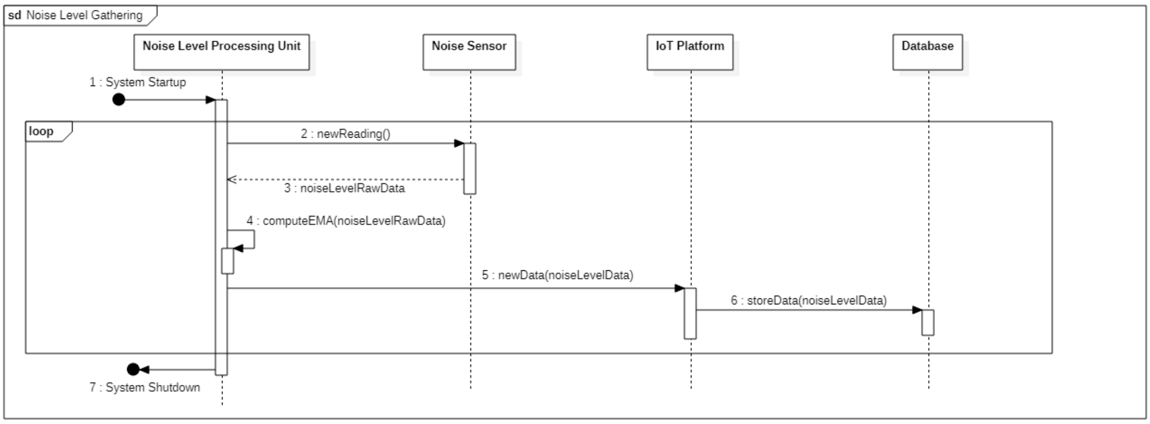


Figure 5.7: Sequence diagram of the the Noise component

The procedure for gathering and storing the DOA data is similar, yet with different components in action. The DOA Processing Unit and the IoT Platform are the components n charge of the process, as shown in the sequence diagram of Figure 5.8. From the startup to the shutdown of the system, the DOA Processing Unit performs a loop of calling the DOA Sensor for data and sending it to the IoT Platform once the sensor replies. Then, the IoT Platform handles the storing of the data in the database component.

The process of gathering the occupancy data, represented by the sequence diagram in Figure 5.9 is controlled by the Card Reader Processing Unit and the IoT Platform. As shown in the sequence diagram, the process starts when one of the room occupants uses his ID card on the Card Reader. The card reader sends information to the Card Reader Processing Unit that an occupant with a specific card is either leaving or entering the room. The Processing Unit checks if the occupant was already inside the room. If so, it assumes the occupant left the room and, if not, it assumes the occupant entered the room. The Card Reader Processing Unit then calculates the number of occupants in the room at that moment. It sends that information to the IoT Platform, which ensures the data is stored in the database component.

The process of changing the colour output of the LED light bulbs is ensured by the

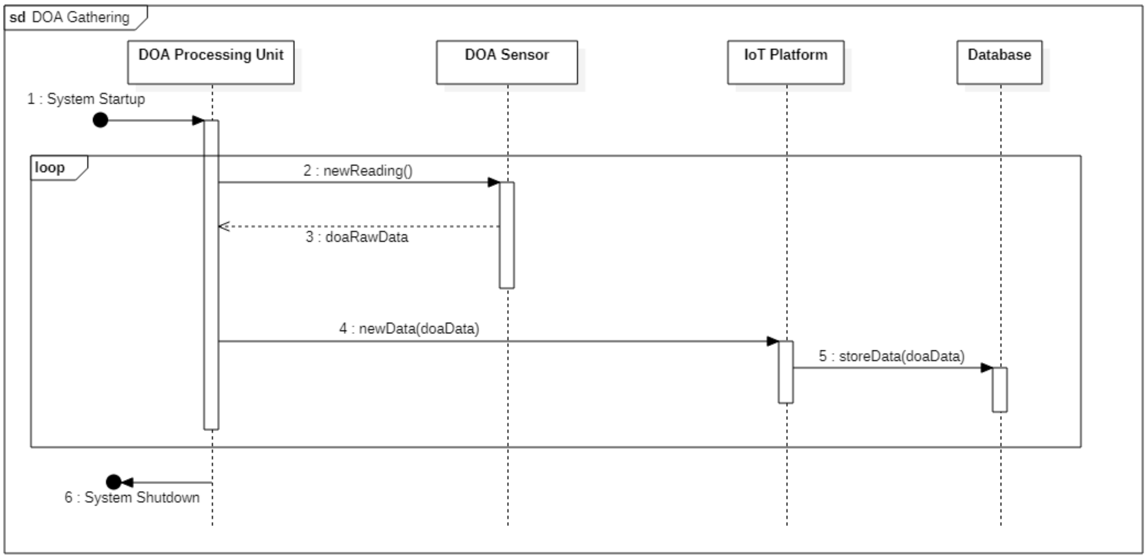


Figure 5.8: Sequence diagram of the the DOA component

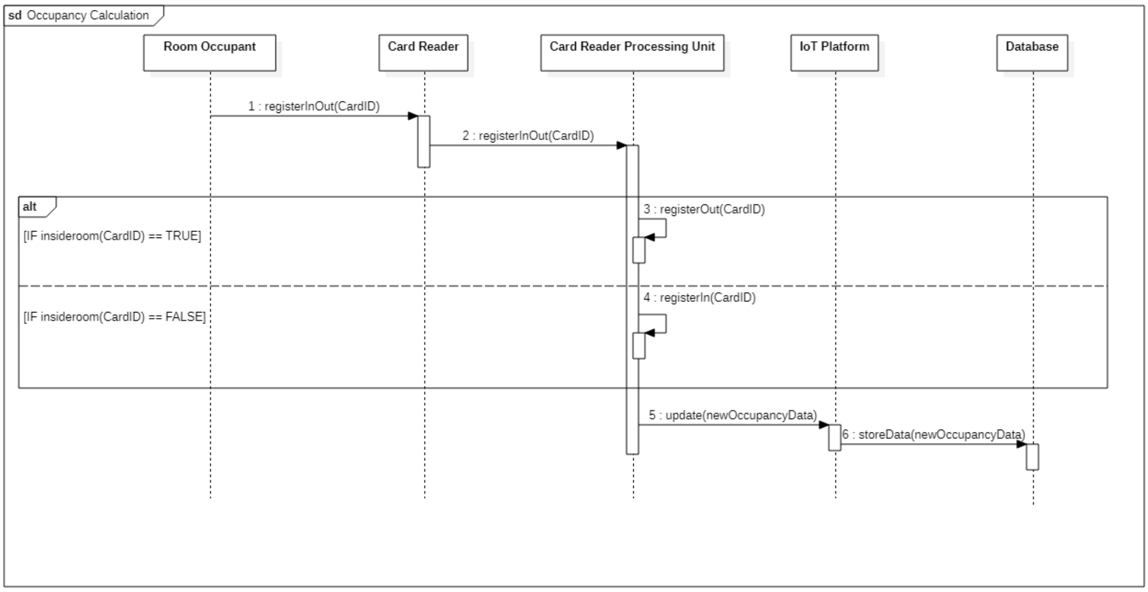


Figure 5.9: Sequence diagram of the Occupancy component

IoT Platform and the Light Processing Unit. As shown in the sequence diagram of Figure 5.10, the process starts with the IoT Platform sending the Processing unit the data of the desired new state of the light bulb. This data indicates if the state of the lamp is to indicate "Medium Noise Level"or "High Noise Level", or if the bulb is to be turned off, indicating "Low Noise Level". Upon receiving such data, the Processing Unit sends the correct signal to the LED light to update the current state to the desired one.

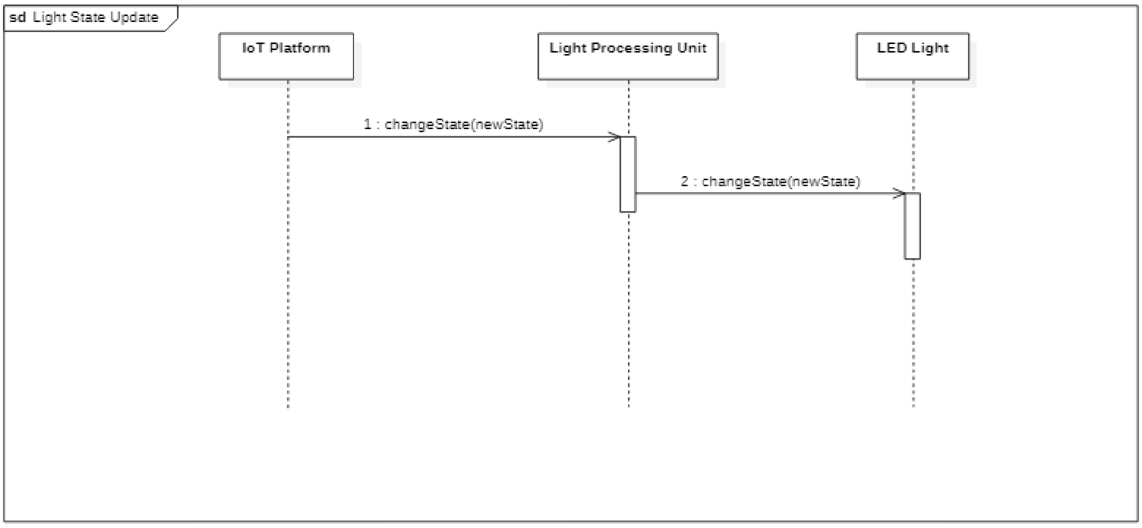


Figure 5.10: Sequence diagram of the Light component

The Noise Controller is the component responsible for interpreting all the gathered data (noise levels, DOAs and occupancy) and making decisions on the actuator's action (Lights state). Figure 5.11 shows the sequence diagram for the decision-making process, involving the IoT Platform, the Noise Controller, the Controller Web Application and the Database components. The process consists of a loop, looping for as long as the system is operational. The Noise Controller starts by calling the IoT Platform for data on the most recent data of all the noise levels sensors. Upon reading the data from the Database, the IoT Platform sends it to the Noise Controller, which then analyses it. This analysis can originate three distinct outcomes.

- If only one of the noise level values is above the established noise level threshold, the Noise Controller checks the severity state of noise production associated with that LightID. If a change of state of the light bulb is in order, the Noise Controller notifies the IoT Platform about it. Then, the IoT Platform updates the light's state by the process described previously (Figure 5.10).
- If more than one of the analysed values are above the established threshold, the Noise Controller calls the IoT Platform for the DOA data associated with the analysed Noise Level Data (regarding time). After reading this data from the Database component, the IoT Platform forwards it to the Noise Controller. The Noise Controller checks this data to ensure that none of the analysed noise level values is a

false-positive. The values can be false positives if, for example, the noise produced by one group is so high level that exceeds the thresholds in multiple sensors. The Noise Controller then checks the severity state of noise production associated with each of the responsible groups and proceed to inform the IoT Platform of the need state changes in the Light components. The IoT Platform updates the light's states by the process described previously (Figure 5.10).

- If none of the analysed values is above the established noise level threshold, the system proceeds in the loop.

The Noise Controller keeps a value for severity for each group of room occupants associated with a noise sensor. Every time that sensor captures noise levels above the established threshold, that value is incremented to a maximum of 15. It is decreased every time the sensor captures data below the same threshold (to a minimum of 0). The Noise Controller uses this value to assess the need for a change of state of the LED light. The lights can have three states:

- **Low noise level** - When the severity value is between 0 and 5. The lamp will be off.
- **Medium noise level** - When the severity value is between 5 and 10. The lamp will display an orange colour with medium intensity.
- **High noise level** - When the severity value is between 10 and 15. The lamp will display a red colour with high intensity.

The cap at 15 prevents the value to grow indefinitely. If there was no maximum limit, the time it would take for the system to transition from a high noise level state to a medium noise level state would be proportional to the time the system spent at the high noise level state, which is not the desired system behaviour. This functionality would only degrade from the system responsiveness. Nonetheless, this maximum value can be lowered if we feel the need to make the system behave more responsive or increased if we feel the opposite and want to delay the system state change.

The next steps of the loop represent two interactions between the Controller Web Application and the Noise Controller. The Controller Web Application, as explained in the upcoming Section 5.5.3, has many functionalities. The key functionality related to the control of the system is the possibility of an administrator of the system to change any desired settings through the Controller Web Application, which then sends the Noise Controller a message bearing the desired changes.

5.5.1 WSO2 IoT Server

We choose the WSO2 IoT Server as the IoT Platform to implement our CPS. As explained in Chapter 3, the choice was based on the works of Pedro Simão [40] and João Cambeiro

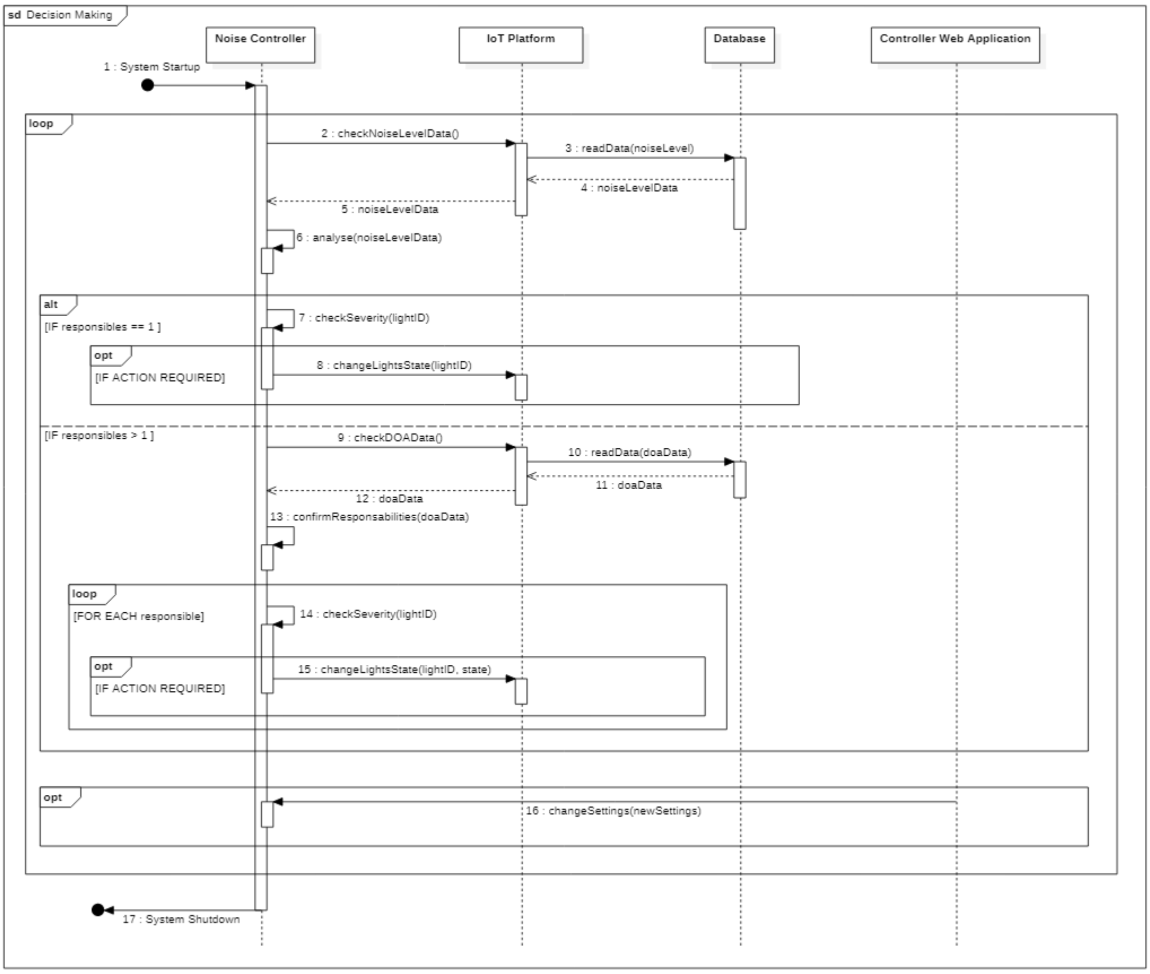


Figure 5.11: Sequence diagram of the the Main Controller

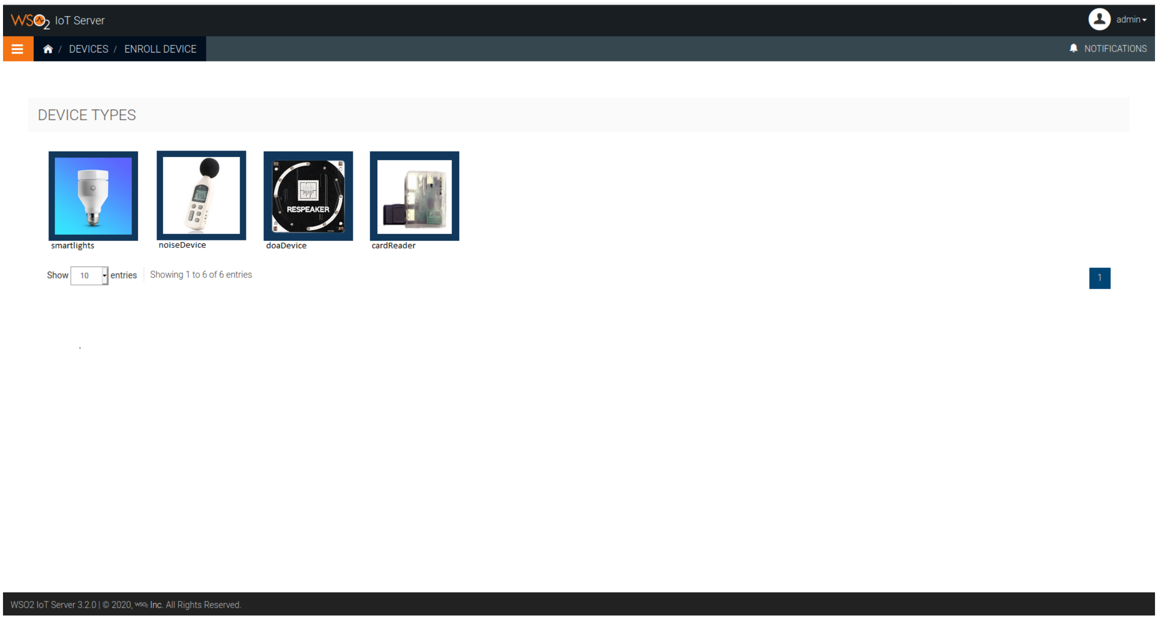
[4], in which they compare it with similar services in the context of an equivalent research project to ours.

The WSO2 solution provides functionalities such as user, device and Application Programming Interface (API) management, real-time data analytics, MySQL integration support and a web application to access all of these functionalities easily. Paired with the IoT platform, we implemented a MySQL relational database to store all its data. Both the WSO2 IoT Server platform and the MySQL relational database are deployed in servers provided by the Informatics Division of Faculdade de Ciências e Tecnologia. These servers are configured to use certificates provided by the Informatics Division of Faculdade de Ciências e Tecnologia, ensuring the safety of the data being exchanged between the IoT platform and the device and the data stored in the database. These certificates include Secure Sockets Layer (SSL) protection.

The WSO2 IoT solution possesses three main components. The IoT Core is the component responsible for handling the devices, APIs, applications and supports the Web Application and the device's plugins. The Analytics Core is the component in charge of gathering the data arriving from the devices and supports different methods of data streaming to achieve it. It is the component that manages the analysis of the data in real-time. The third component is the Broker, which handles the communications. This component is responsible for enabling secure communication between the different end-points of the system by ensuring the authentication of the Message Queuing Telemetry Transport (MQTT) clients and the data encryption policies.

As explained previously, our CPS implementation counts with four distinct device types: noise level sensors, DOA sensors, card readers and LED lights. To integrate these devices with the WSO2 solution, we implemented their respective plugins using Java programming language, following the device maven archetype provided in the WSO2 documentation [47]. This maven archetype consists of five packages: Analytics, API, UI, Feature and Plugin. The Analytics package is where the device data streams and related databases are defined. The API package contains the implementation of the device type API and the permissions required for access to the API endpoints. The UI package contains the implementation of the User Interface in the WSO2 web application, in which the user can see the data of the device. The Feature package contains the definition of the device data sources. The Plugin package consists of an OSGi bundle integrated with the WSO2 Connected Device Framework. This package's content is used to generate the artefacts that allow the integration of the device type with the IoT Core.

After developing the four device type plugins, they were deployed to the WSO2 IoT Server instance. After deployment, the administrator of the system can access the IoT Platform via the Web Application and create devices of the deployed device types, as shown in Figure 5.12.



Showing 1 to 6 of 6 entries

WSO2 IoT Server 3.2.0 | © 2020, WSO2 Inc. All Rights Reserved.

Figure 5.12: WSO2 IoT Platform interface for adding new devices to the system

When a device is created through the WSO2 web application interface, the IoT platform generates a file containing the device properties, as shown in Table 5.1.

Property	Description	Example
owner	The WSO2 IoT Server user that created the device	admin
deviceId	An alphanumeric string that identifies the device	mn32njb2bjbn
device-name	The name of the device	DOA Sensor 1
device-type	The type of the device	doaDevice
mqqt-ep	MQQT Endpoint	tcp://192.168.1.XXX:XXXX
https-ep	HTTPS Endpoint	https://192.168.1.XXX:XXXX
auth-metod	The type authentication method used by the device	token
auth-token	Authentication token	XXXX-XXXXXX-XXX...
refresh-token	Refresh toke, used to update the authentication token	XXXX-XXXXXX-XXX...
application key	Application authentication key	XXXX-XXXXXX-XXX...

Table 5.1: Device properties generated by the WSO2 IoT Server

These properties will be used by the Agents of the devices to ensure communication between the device and the IoT platform.

5.5.2 Agents

Agents are the intermediate software between the WSO2 IoT Server and the physical device. Using the device properties file, generated at device creation, the Agents handle the communications between server and device.

They are also responsible for preprocessing the raw data gathered by the devices. The methods used vary between agents, but the goals of the preprocessing are (1) translating the data to a format that the server expects and (2) ignoring useless data that the physical device might gather such as bad readings and useless meta-data.

For our implementation, we developed four distinct agents:

- **Noise Level Agent** - Implemented in C programming language, this Agent reads data from the Noise Level sensor via a USB connection. It gathers the packets containing the noise level data from the connection, applies the EMA and sends the data to the WSO2 IoT Server.

- **DOA Agent** - The DOA agent is implemented in the Python programming language. It makes use of the Python modules provided by the manufacturer to gather the data from the DOA sensor and sends it to the server.

- **Card Reader Agent** - Implemented in Java programming language, this Agent handles the data gathered by the Card Reader and sends it to the server.

- **LifX LED Lights Agent** - This Agent, implemented in Java programming language, uses the Lifx LAN Protocol to gather data from the LED LifX light bulbs and to change their state. The gathered data includes the power state (on/off), the brightness value and the colour value (hue, saturation and luminance). The state changes can also alter all of these values.

The Agents will be running in what we denominate processing units, which consist of multiple Raspberry Pi 3 with 1GB of RAM (Figure 5.13). Although having low computation power when compared to a standard computer, the Raspberry Pi 4 has enough power to handle the Agent code execution and had the benefit of being small in physical size, becoming easy to hide. Also, with the use of its Wi-Fi capabilities, it enables the transmission of the processed data to the control layer of the system without the need for an Ethernet cable connection.

Figure 5.13: Raspberry Pi 4 Model B[4]

5.5.3 Controller Web Application

The Controller Web Application was implemented with Spring Boot, making use of tools such as Java programming language, HTML and ThymeLeaf template engine. Its main goals are: (1) provide a back-end controller for the implemented CPS ensuring the system logic is ensured, (2) provide an administrator back-office where they can manage the system and its users, and (3) an interface for the interactions of the users with the system. We also implemented a MySQL database to store all the relevant data of the Web Application, such as user data. Both the application and the database are deployed in servers provided by the Informatics Division of Faculdade de Ciências e Tecnologia. Similar to the one hosting the WSO2 IoT Server, these servers are configured to use certificates provided by the Informatics Division of Faculdade de Ciências e Tecnologia, ensuring the safety of the data being exchanged between the IoT platform and the Controller Web App and the data stored in the database. These certificates include SSL protection.

To achieve the first goal, the Controller Web Application has routines that check the data from the IoT platform using the API endpoints. From this data, the Controller ensures the system behaves as expected. The Controller is also responsible for prompting the IoT Platform with the needed actions, which the IoT platform forwards to the respective Actuator.

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[4] Figure from `https://www.raspberrypi.org/products/`

The administrators have access to a specific instance of the Controller Web App, consisting of a back-office for the implemented CPS. In this back-office, the administrators can:

- Turning the full system on and off, or just a fraction of it. This is useful for handling unexpected situations which might require the system to be shut down periodically. The administrators can turn the system on and off easily, instead of having to manually shut off the server.
- Manage users by adding, removing and assigning them to groups. Since the users will be divided into workgroups, an Administrator must configure these associations in the Controller Web Application, *e.g. "Group 1 is composed by user1, user2, user3, user4 and user5."*.
- Manage the system by adding or removing device, as well as manage their roles. At boot, the Controller Web Application needs to be configured by an Administrator to have the alphanumerical string that identifies all devices registered in the WSO2 IoT Server. This configuration enables the Controller to make the access the correct API endpoint when checking the gathered data. The Administrator also has to indicate to the controller how the system is deployed: which noise level sensor and LED lamp is associated with which group of users, *e.g. "The noise sensor jal62d1s5nm and the LED lamp tret1efgd35g are associated with group 1"* and the configuration of the DOA ranges, *e.g. "Regarding DOA device ksn278db87db, values between 0 and 90 correspond to group 1, values between 90 and 180 correspond to group 2, values between 180 and 270 correspond to group 3 and values between 270 and 360 correspond to group 4"*
- Schedule office events. The Administrator can create a type of events that require the system to change its Control Logic temporarily. Once the scheduled event starts, the system changes to the "meeting mode". This mode is crucial in a context where the different occupants of the office room have to discuss a subject common to all. These circumstances usually imply noise levels above average and require the occupants to gather in a specific zone of the office (outside their designated workspace), which also requires our system to change its approach to detecting high noise levels and their origin.

The users have access to a more limited instance of the Controller Web Application, in which they have access to fewer functionalities, to safe-keep the system from human error. Standard users can use the web application to check the scheduled events and they can suggest events, which will require confirmation by an Administrator to be scheduled.

This web application was designed with future works in mind, which are explained in detail in Chapter 9, that did not embody the scope of our studies. As an example, functionalities to provide tools for the users to facilitate the endorsement of Software Engineering methodologies in their works can be implemented with relative ease.

5.6 Deployment

For the deployment of our CPS, we took into consideration a 5-layer architecture, as shown in Figure 5.14.

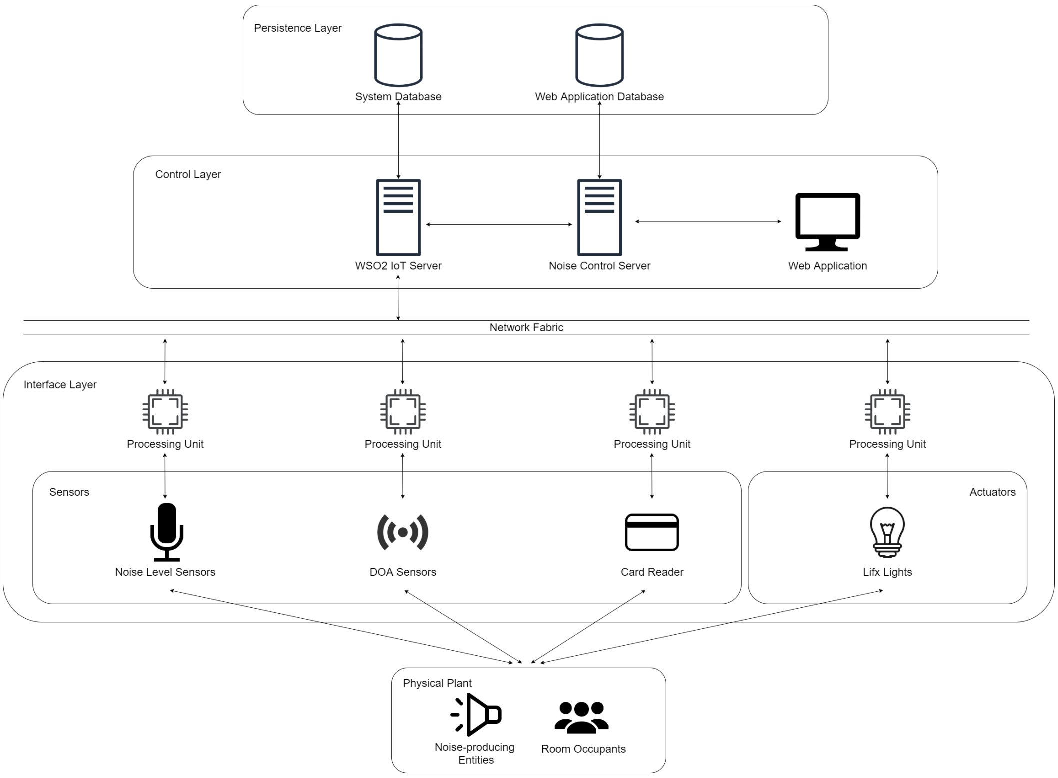

Figure 5.14: Overview of the CPS with layer identification

The physical plant consists of the occupants of the office room and other noise-producing entities. They are at the same time the producers of data, by generating sound signals, and the ones affected by the actions of the actuators.

The Interface Layer contains the Sensors, the Actuators and the Processing Units and represents the frontier between the physical and the cybernetic parts of the system.

The control layer consists of the WSO2 IoT Server, the noise control server and the Controller Web Application. These three components having the common goal of ensuring the system behaves as expected.

The network fabric layer connects the interface layer and the control layer, being the critical enabler of communication between layers.

The persistence layer consists of two databases. The System Database holds all the data gathered by the sensors and processed by the system. The Web Application Database holds the data regarding the Controller Web Application, such as user data.

The placement of each physical component of the system will depend on the layout of the office room. As an example, Figure 5.15 shows how the components should be deployed for the experiment to which we propose guidelines, explained in detail in Chapter 7. This specific layout consists of eight noise level sensors, one per workspace, for noise level data gathering, three DOA sensors to ensure that only responsible groups are notified for their high noise level, and one card reader sensor registering entrances and exits.

The experiment has a second room with a different layout, shown in Figure 5.16, but not due to the different layout of the room. In our experiment's particular context, this room poses as a point of comparison between a room equipped with our system, and a standard office room. For that reason, the room will only have sensors to gather data thus the difference in layouts, being equipped with three noise level sensors

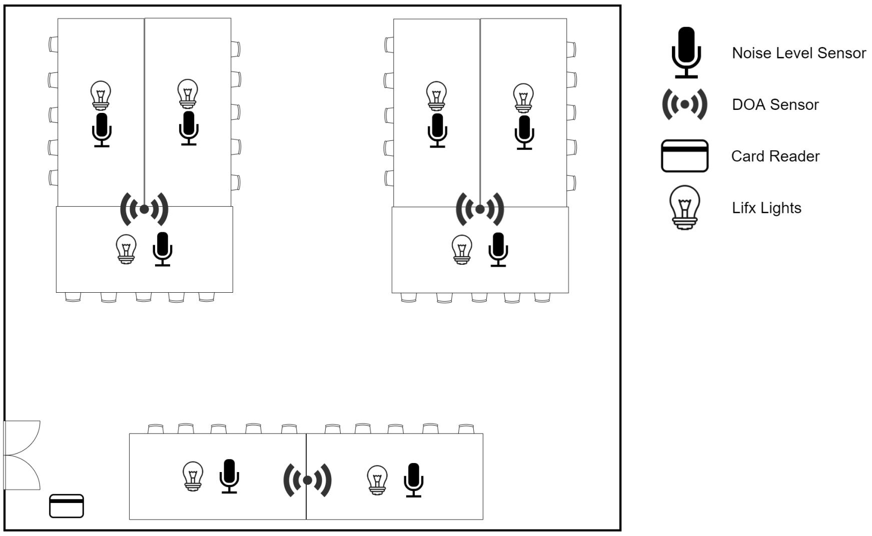

Figure 5.15: Overview of the smartOffice room layout, used for the experiment

According to the previously mentioned choices, the hardware used in the deployment of our CPS implementation is summarised in Table 5.2.

Role	Hardware	Figure
Processing Unit	Raspberry Pi 4 (1GB)	Figure 5.13
Sound Level Sensor	GM1356 Digital USB Noise Meter	Figure 5.2
DOA Sensor	ReSpeaker 4-Mic Array	Figure 5.3
Light	Lifx Lights	Figure 5.5
Card Reader	Card Reader [31]	Figure 5.4

Table 5.2: Hardware used to implement the system

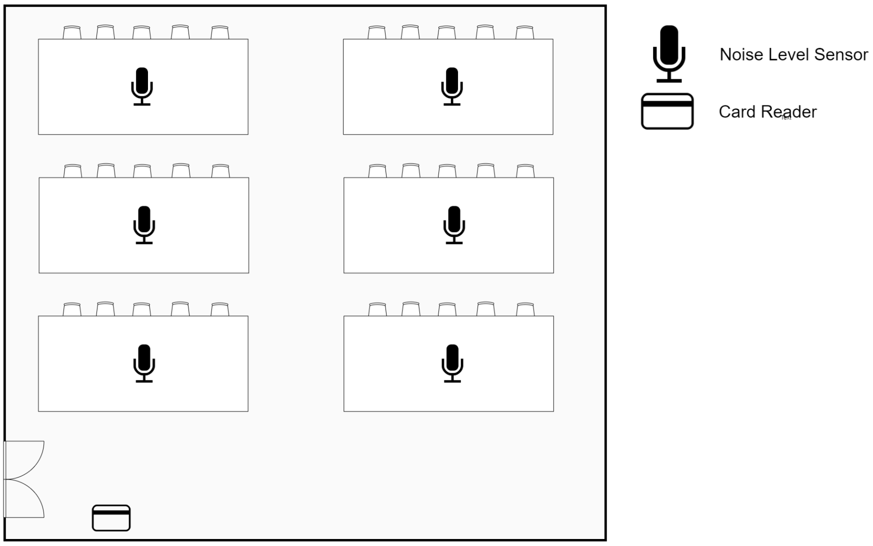

Figure 5.16: Overview of the standard room layout, used for the experiment

Chapter 6

Integration Tests

This chapter explains in detail the integration tests. Section 6.1 provides some context to the tests and section 6.2 describes the test scenarios and some conclusions after the analysis of the results.

6.1 Context

Before deploying our CPS to its full scale, we decided to make a smaller deployment first to ensure it met all the functionality requirements. Using a smaller room, we deployed our system following the layout shown in 6.1 and designed five possible scenarios that tested every element and functionality of our system. Since our project is highly extensible and scalable, the test results performed in this context are show some degree of validity for full-scale deployment with more physical components, with a different office room layout. However, the scale of the office bring some threats to this validity that must be approach in the context of each specific office layout and dimensions. As an example, with the increase of the room size and occupants, the presence of white noise can stimulate the occupant to speak louder than we estimate when designing the system, which might required a slight adjustment of the thresholds. The number of devices and their disposition must also be designed for each room layout, since a misplaced sensor can tamper with the system's capacity for detecting the correct source of the noise.

6.2 Test Scenarios

We designed five distinct scenarios to test the system. We conceived these scenarios taking into consideration expected use-case situations.

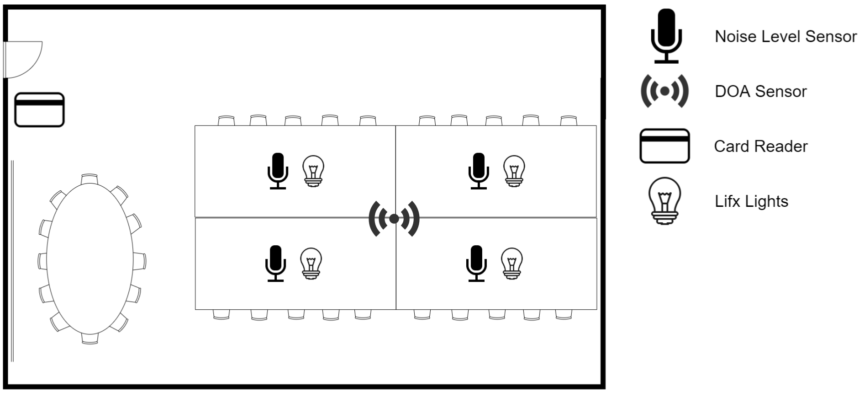

Figure 6.1: Plan of deployment for the integration tests

We then observed the system's behaviour when facing each of these scenarios to ensure its functionalities were working as intended.

In all scenarios, we considered that four groups (teams) of office workers occupy the room, with a workspace for each team. The noise-generating behaviour of these groups was simulated using a speaker per workspace, producing the desired noise levels to test each scenario.

6.2.1 Scenario 1

In the first scenario, all the groups inside the room are respecting the noise level threshold, except one, as shown in Figure 6.2.

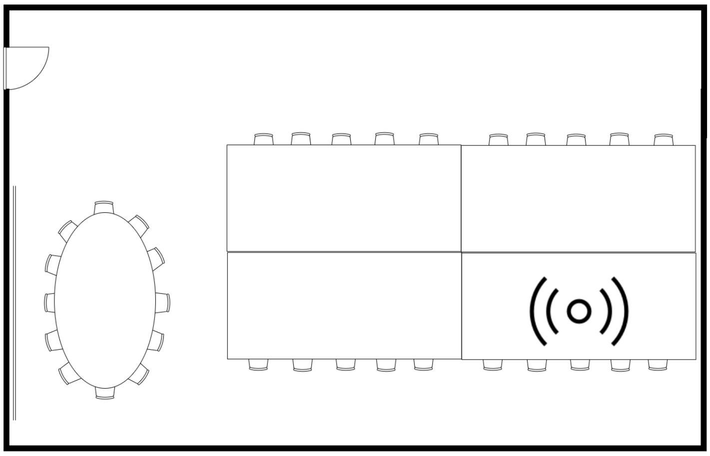

Figure 6.2: Scenario 1

The noise sensor in the designated workplace captured the high noise level, as shown in Figure 6.3. In the Figure's graph, the red line represent the noise level threshold and the green rectangle marks the time window in which the group was exceeding the threshold.

Figure 6.3: Noise Sensor 1 Data (Scenario 1)

Since this was the only noise sensor capturing noise levels above the threshold in a specific time window, there was no need to use the DOA sensors to confirm if the group was responsible for producing such noise levels. Since the noise level persisted above the threshold for more than five seconds, the system notified the group by changing the light colour to orange. Five seconds after, since the sensor was still capturing values above the noise level threshold, the group received a new notification with the light changing to a red colour. After this, the group reduced their noise level, which caused the system to roll back the warning, making the light go orange after five seconds, and back to turned off after five more seconds.

6.2.2 Scenario 2

The second scenario, as depicted in Figure 6.4, has more than one group producing noise levels higher than the threshold.

Figures 6.5 and 6.6 represent the data from the two noise sensors corresponding to the two groups responsible for the high noise levels. The red lines in both Figures represent the noise level threshold and the green rectangles the time frame we are analysing. In the same figures, there are two more occurrences of the same scenario. We chose the time frames highlighted in the green rectangles for no specific reason, as either of the three occurrences could be used to test this scenario. We can verify how both sensors record values over the threshold in the highlighted time frame.

In order to confirm that both groups are indeed responsible for producing high noise levels, the system analyzes the respective DOA sensor data, shown in Figure 6.7, and chose the group responsible for producing more noise. In the graph of Figure 6.7 there are two highlighted ranges of values: the first range, identified by the blues horizontal lines, highlights the DOA values associated with the noise sensor 1 and the second range, identified by the red horizontal lines, highlights the DOA value associated with the noise

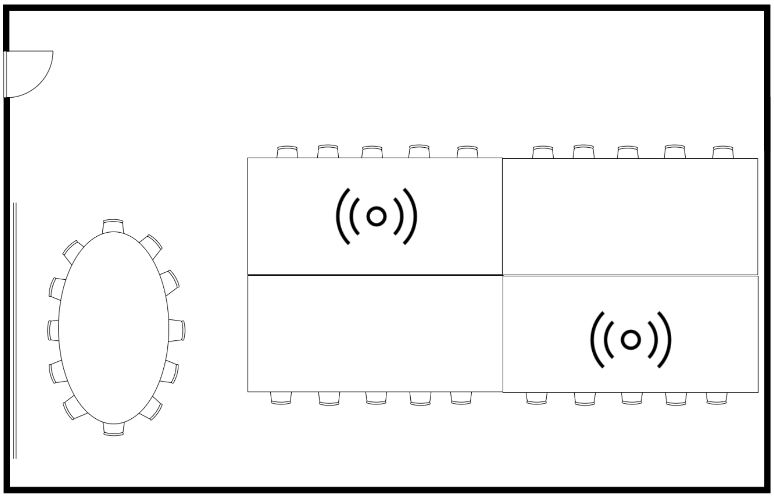

Figure 6.4: Scenario 2

Figure 6.5: Noise Sensor 1 Data (Scenario 2)

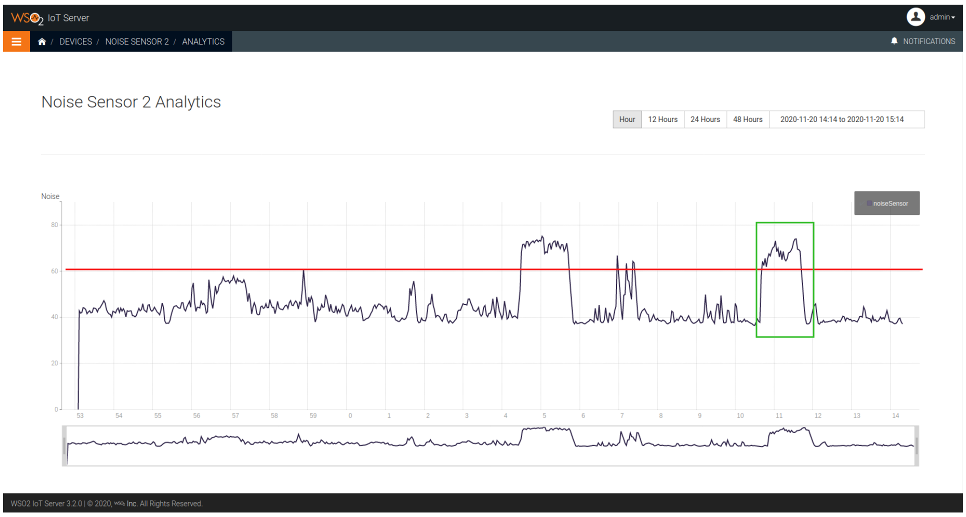

Figure 6.6: Noise Sensor 2 Data (Scenario 2)

sensor 2. The green oval marks the time frame which we are analyzing. Since there are values matching both ranges of values, the system chooses the first responsible group by majority of values inside the range, choosing noise sensor 1. Once that group was identified and adequately notified via LED lamps, the system checks if the second suspected group was a false-positive. After rechecking the DOA data, and confirming the existence of values inside the group's range, the system considers the second group also responsible for producing high noise levels, proceeding to send the notifications.

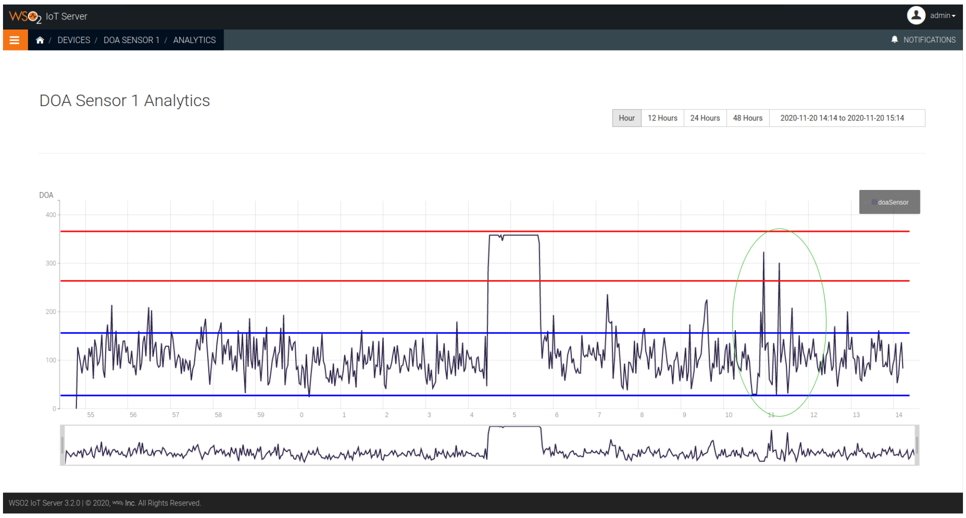

Figure 6.7: DOA Sensor 1 Data (Scenario 2)

From this point on, the system behaves as in scenario 1, where the system rolls back the notifications as the groups lower their noise level.

6.2.3 Scenario 3

The third scenario is similar to the first one. We also had all the groups respecting the noise level threshold, except one. However, in this scenario, the group making noise was producing such a high noise level that surpassed the threshold not only on the group's corresponding sensor but also in the neighbour's sensor as well, as shown in Figure 6.8.

These circumstances can be misleading and must not be confused with scenario 2, where both groups were responsible for the production of high noise levels. Figures 6.9 and 6.10 show the data gathered by both sensors. The red lines represent the noise level threshold and the green rectangle the time frame analysed. We can see how both sensors captured above-threshold noise levels in the highlighted time frame.

Figure 6.11 shows the data gathered from the DOA sensor, with the red lines indicating the range of values associated with noise sensor 2 and the green oval the time frame being analysed. We can see how the high noise levels were unequivocally generated from the workspace where the noise sensor 1 is deployed. Using this data, the system chose the group associated with the noise sensor 1 when looking for the group responsible for

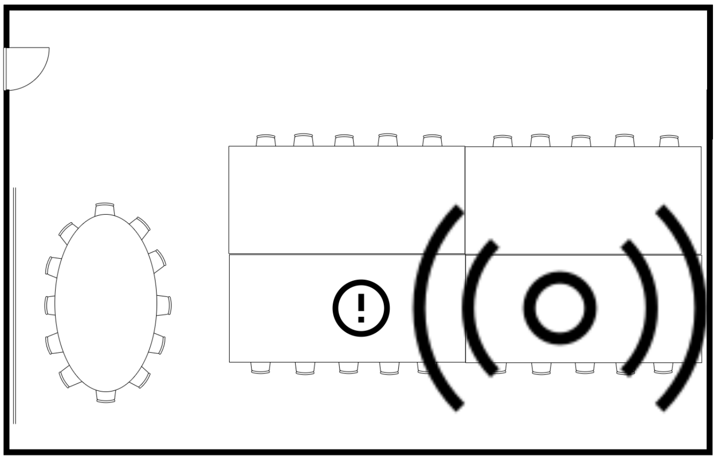

Figure 6.8: Scenario 3

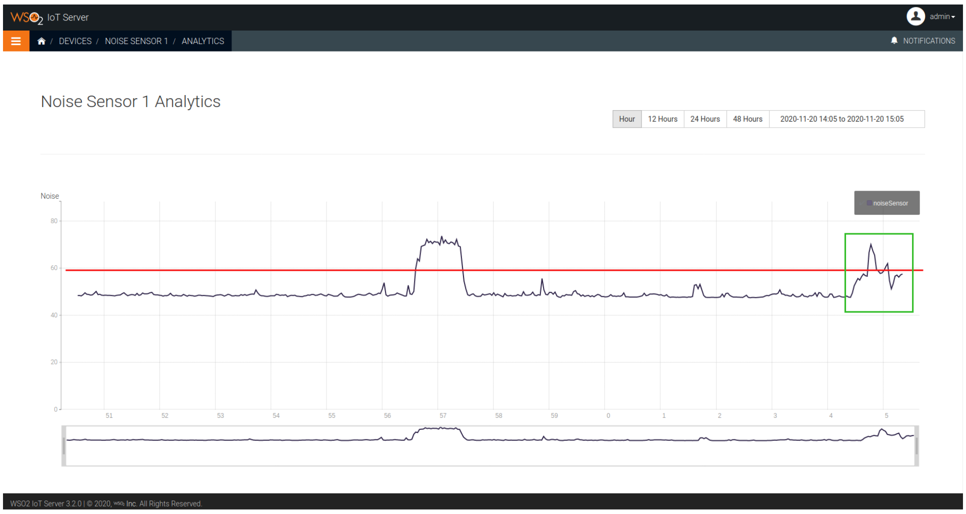

Figure 6.9: Noise Sensor 1 Data (Scenario 3)

producing the largest amount of noise, and sent the notifications, like in scenario 2. After this, the system checked the DOA data again, confirming if the data correspondent to the second group was a false-positive. Since the DOA data indicates that the second group is not responsible for the production of high noise levels, the data was considered a false-positive, and the system deployed no notifications to this group's workspace.

Regarding the first group, the system behaves as in scenario 1, where the system rolls back the notifications as the groups lower their noise level.

6.2.4 Scenario 4

The fourth scenario corresponds to the activation of the "meeting mode" where one or more groups would have a scheduled meeting in the meeting area, as represented in

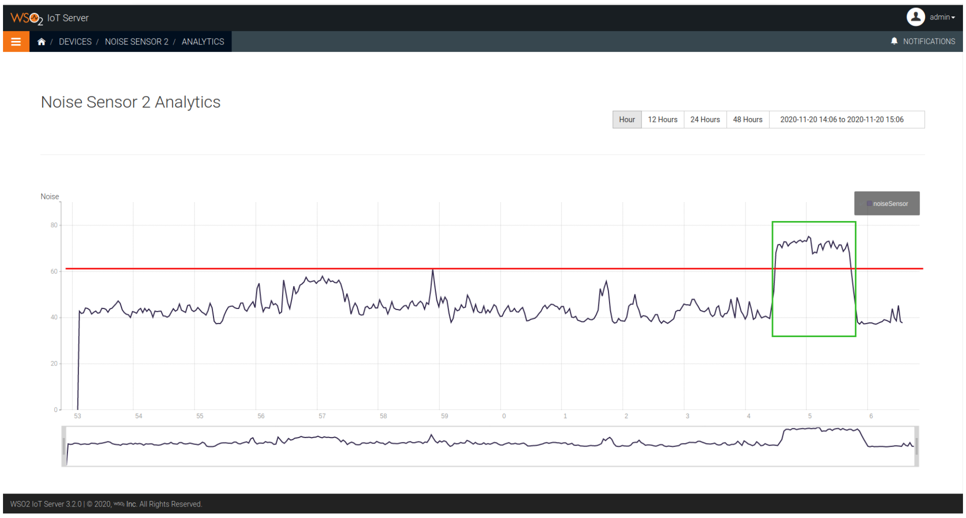

Figure 6.10: Noise Sensor 2 Data (Scenario 3)

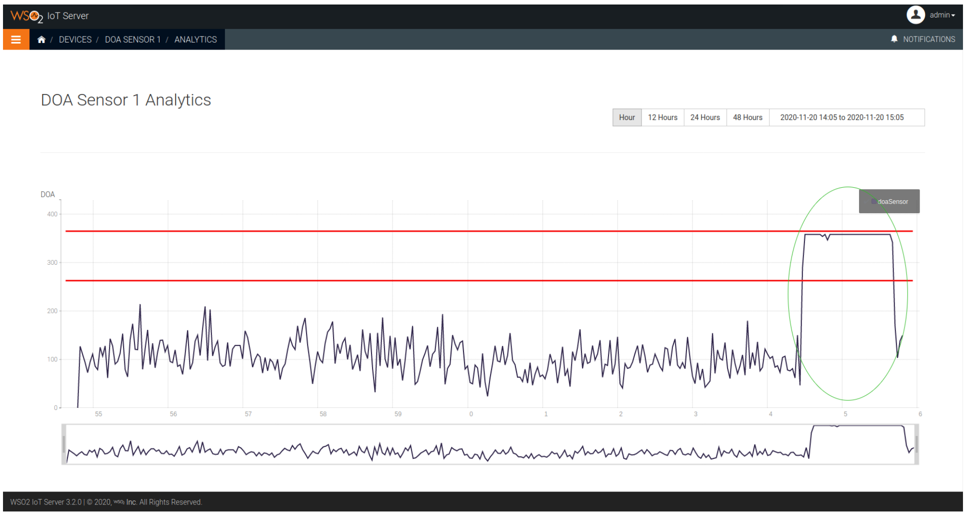

Figure 6.11: DOA Sensor 1 Data (Scenario 3)

Figure 6.12.

Since these meetings serve the purpose of allowing boundless communication between groups, in order to allow discussion of planning or execution of the project, it makes no sense for the system to keep checking if the room occupants are violating the noise level thresholds like usual. When a scheduled meeting starts, the system enters the event routine, ignoring the data from the noise sensors. Once the meeting is over the system goes back to its standard routine, checking the noise sensors' data for noise level threshold violations. However, the way the system detects the end of these events is a subject of discussion.

On one hand, we can ask the creator of the event for a estimated duration time. The system would go back to its routine once the duration of the event expired. This solution introduces problems when the duration of the meeting either extends or falls short of the estimated one. If the meeting was shorter than expected, the user would have to manually

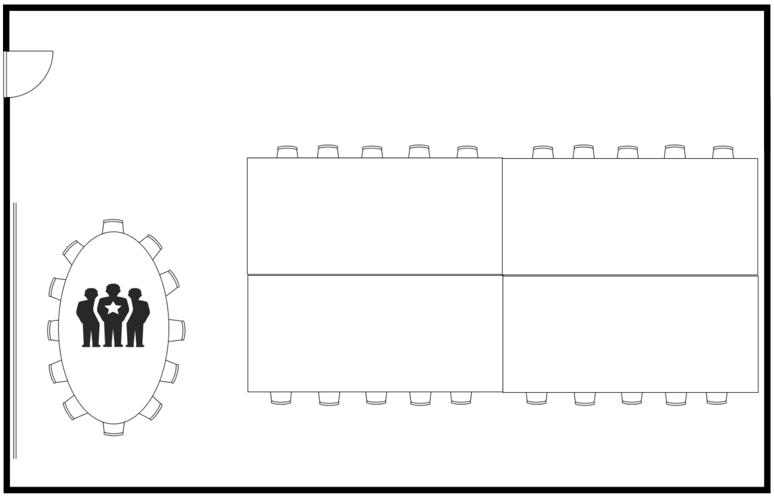

Figure 6.12: Scenario 4

end the event via the Web Application. If the duration extends the estimated, the problem is even worse, with the user having to create a new event on the Web Application.

On the other hand, we can have a semi-automated mechanism by changing the event routine of the system. Instead of ignoring the noise sensor data, we would assume the users left their workspaces to meet in the meeting area. The system would assume the meeting is over when the sensors start to capture intermediate noise levels again. The problems with this approach are that (1) we have to assume that all the occupants of the room would move from their workspace to the meeting zone for the duration of the event, which does not necessarily happen and (2) we have to assume that even the noise level sensors of the workspaces closer to the meeting zone would not capture the noise levels produced by the meeting participants.

We chose to follow the first approach due to fact that the solutions for the problems brought forth by the second approach do not fit the context of our studies. Nevertheless, in an hypothetical context in which we could assure that (1) all the occupants of the room would be present in the meeting area or that (2) the office would be equipped with some kind of physical barrier to prevent the noise of the meeting area to be captured by the noise level sensors of the open space office, the second approach would improve this system's feature by requiring less human interaction with the Web Application for it to work.

6.2.5 Scenario 5

The fifth and last scenario corresponds to the behaviour of the system when the room is empty or not. As represented in Figure 6.13, the card reader next to the door will register the entrances and exits of the office, as shown by the graph in Figure 6.14. The green oval in the figure highlights the point when the room was no longer empty and the red oval highlights the point when the room was empty again.

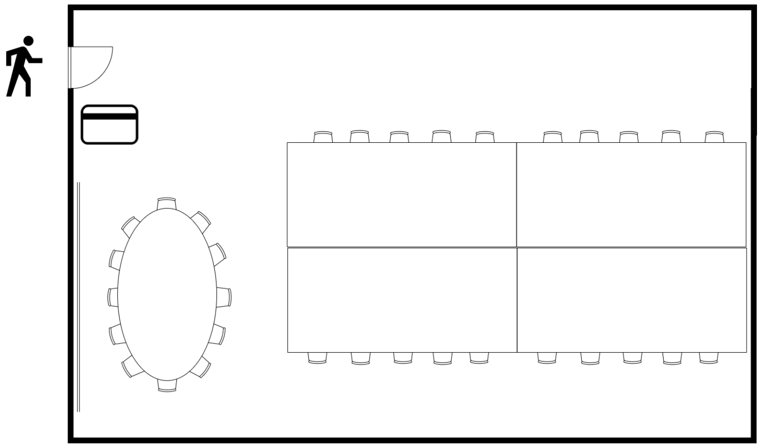

Figure 6.13: Scenario 5

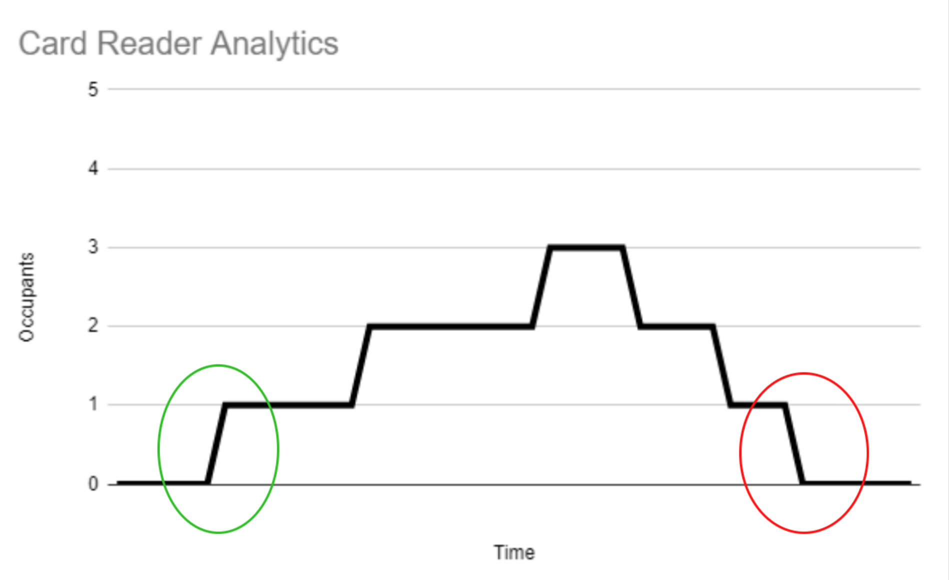

Figure 6.14: Occupancy Data

The system checks the occupancy data periodically and, when the room is empty (red oval), the system interrupts its standard routine, to save energy. When the office is empty and a person enters the room (green oval), the system goes back to the standard routine, checking the noise sensor data for noise level threshold violations.

6.2.5.1 Assumptions

The mechanism our system uses to handle energy efficiency, using data on the room occupancy to turn off the system when the room is empty, makes some assumptions on the behaviours of the office occupants. These assumptions can represent a threat to the validity and efficiency of this mechanism in a real world scenario.

The occupants of the office must always use their identification cards on the card reader sensor upon entering or exiting the office room, with no exception. If more than one person enters or exits the room at the same time, all of them have to individually use the identification card on the card reader sensor. The system must assume these behaviours to ensure that (1) the system does not interrupt its routine when there are still occupants inside the office room, (2) the system does not keep executing its routine when the office room is empty and (3) the gathered occupancy rate data, which we will use to draw conclusions for our study, is representative of the actual occupancy rate.

These assumptions might not be valid in a real office environment since the accuracy of the occupancy data is totally dependent on the behaviour of its occupants. Some occupants of the office might belittle the action of using the identification card on the card reader since, for example, the system is already following the normal routine when they arrive or if they are in a hurry to leave the office. This can induce inaccuracy in the gathered occupancy data and problems like the system assuming someone is still inside when in reality the room is empty and vice-versa.

Although there are solutions that would allow us to monitor accurately the presence of occupants in a room, they are well outside the scope of our work in this dissertation. A simple solution would be to use a mobile application installed on the smartphones of all the works who would enter or exit the office room. The office room can then be equipped with special wifi devices that work like antennas, and signal the application that the user is inside the room and in which part of the room, by triangulating the different signals arriving from all the antennas in range. The application would then change data with a server that would compute the occupancy rate of the room.

Although it sounds like a better solution than the proposed, in which we are able to accurately monitor occupancy rates without being dependent on the actions of its occupants, it represents some threats to the privacy of the workers. First, they all must agree to install the application on their smartphones, and second, they must agree to be tracked inside the office environment. Furthermore, the occupants of the office can also forget their smartphones at home or in the office, thus creating the same type of problem would the identification cards, with the system assuming the room is empty when it is not and vice-versa.

With this in mind, in the scope of our work, we assume that all the room occupants behave flawlessly when entering or exiting the office, using the identification card on the card reader.

Chapter 7

Simulations and Experimental Guidelines

This chapter consists of guidelines to prepare, execute and analyse an experiment on our CPS's effectiveness, accompanied by simulations of some hypothetical scenario. Section 7.1 provides a detailed description and contextualisation of the experiment. Section 7.2 contains an overview of the experiment. Section 7.3 contains guidelines for the setup of the experiment. Section 7.4 presents simulations regarding possible scenarios for average noise level and occupancy rate data. Section 7.5 present the guidelines for the analysis of data gather upon the realization of the designed experiment. Section 7.6 contains a summary of the chapter.

7.1 Context and Description

In the previous chapter, we presented the result of several functionality tests that ensure the system works as intended. However, to truly assess the effectiveness of our CPS in the reduction of noise in open space office environments and its impact on the occupants' productivity, we need to perform an experimental procedure using real data gathered.

This experiment is designed around "Actividade Prática de Desenvolvimento Curricular - Projecto"[1], a subject of the Licenciatura em Engenharia Informática (LEI)[2] lectured at NOVA University of Lisbon. This subject has students working in an open space office environment during a semester and tries to mimic a real office environment, which means not only that it is a good target for the experiment, but also that the conclusion drawn from the said experiment will present some level of validity for "real world"scenarios.

The similarities between the environment of APDC and an open space office of a company also allow us to use some of the data available from prior studies designed

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[1] Practical Activity of Curriculum Development - Project

[2] Computer Engineering Degree

around professional offices, as we will in some of the following sections.

In order to prepare for this experiment, which is outside the scope of our work and can only be performed in the second semester of the upcoming academic year (2020/2021), we made some simulations of hypothetical scenarios regarding the data that will be gathered, and designed an experimental protocol to provide guidelines for the realization of the experiment in the context of a future work.

7.1.1 Work methodology in APDC

When starting the APDC course, students form five-member groups, with a project's subject common to all groups. Each group must develop a web or mobile application (or both) from scratch with the given subject in mind. All groups must implement some key functionalities indicated by the professors in charge of the course. These implications ensure both justice and objectiveness of the evaluation of the students. Nevertheless, the groups have the creative freedom to develop as many extra functionalities as they see fit. Their goal is to develop and deliver the most valuable final product they can produce over the given time.

The main goal of the APDC course is to improve students' full-stack software development skills. To ensure that every student is working on a full-stack scope, every group member must take part and have in-depth knowledge about every task performed in every stage of development. Specialisation in one field of work (*e.g.* back-end developer or front-end developer) should not happen throughout this course.

The second goal of the course is to introduce students to a software development work environment, and teach them how to work in one. The two rooms available for the APDC teams for the duration of the course emulate open-space offices, with each group assigned to a specific workspace. Each workspace contains a computer, power outlets, desk space for five laptops and chairs for all team members.

Before starting to work on the projects, the students attend a sequence of theoretical and practical classes, where they learn the basics about the technologies they will be using and the advised work methods to follow. Doing this provides the students with a starting point for their projects, but they are still allowed to utilise other technologies besides the proposed ones. In either case, the students have upon them the responsibility to research and deepen their knowledge about the technologies they will be using, developing their self-learning skills.

The teams follow an incremental development methodology composed of three increments, with approximately one-month deadlines. The first increment (Alpha version) should contain the core product, with all the required functionalities already implemented. The second increment (Beta version) should contain all the functionalities of the final product, lacking only some refinement and some non-critical bugs to solve. The third and last increment should be the project in its final version. After each increment is delivered, the group must review their work and make the work plan until the next delivery, resulting in an increase of product value with each increment cycle.

7.2 Experiment Overview

The students attending the APDC course are divided into two distinct rooms. As mentioned previously, one of the rooms will represent the office environment with our CPS deployed, designated as smartOffice. The other room will be the control group for the experiment, in which we will install noise sensors to be able to compare the two environments.

Upon the deployment of our CPS, the students attending the APDC course will use the smartOffice room and the standard classroom for the duration of the experiment. The system will continuously gather and store data regarding noise levels, DOA values and changes of state in the LED bulbs. This data will be analysed, during and at the end of the experiment, and will provide the answers to some of our research questions.

7.2.1 Analysis Procedure

The system gathers different types of data while operating. In order to better understand that data and make a good analysis of it, we should take into consideration four distinct scenarios, each focusing on a different aspect of the experiment. Each scenario will answer a specific question, doing so through the usage of different metrics.

- **Scenario 1** aims to answer the question "Is the implemented CPS able to reduce noise?". By comparing the noise level data gathered from the smartOffice and the standard classroom during similar circumstances, we will see if the implemented system has an impact on the produced noise.

- **Scenario 2** is about the satisfaction of the room occupants, trying to answer the question "Do the smartOffice occupants enjoy the office work conditions and the implemented CPS?". The answer to this question will be given by the analysis of a series of questionnaires the room occupants will answer throughout the semester.

- In **Scenario 3** we try to answer the question "Does the implemented noise-controlling CPS improve productivity?" through different metrics. We will use some of the productivity measurement metrics explained previously in Chapter 3 such as retrieving data from questionnaires about the occupants perceived productivity and the value of the student's final product.

- In **Scenario 4** we will focus our analysis on the occupancy data, trying to answer the question "Do people prefer to work in the smartOffice, or at another place?". The questionnaires answered by students from the previous edition of the course identified two problems: (1) most students did not like to work in the classroom and (2) that this was mostly related to high noise levels. With that in mind, answering this question requires us to analyze the occupation rates of the smartOffice room and the occupants' opinions on their working conditions.

7.3 Experiment Setup Guidelines

This section presents the guidelines for our simulated experiment, as well as for future experiments to be conducted using the toolkit developed in this dissertation. Following these guidelines, we will try to answer the research questions identified in the previous section.

7.3.1 Preparation

Before the experiment starts, the students of the APDC course need to attend a lecture on how to behave during the experiment execution. The professors in charge of the course also need a briefing on how the system operates.

7.3.1.1 Students

In APDC, the students will be distributed by the two different rooms: the smartOffice and the standard room. All students should receive a briefing according to their assigned rooms. In both rooms, the students should be informed that they will be providing data to an experiment during the semester. They should also be asked to pass their student's card on the card reader every time they enter or leave the room.

The briefing for the students from the smartOffice should serve as a tutorial on how to interact with the CPS, what each of the colours of the LED lights means, how they should react to each colour and the importance of using their identification card on the card reader when entering or exiting the room. Their briefing should also explain the role of the Web Application for the smartOffice and how to use it.

The briefing for the students from the standard room, which represent the control group for the experiment, should not contain information on how to interact with the smartOffice but should underline the importance of using their identification card on the card reader when entering or exiting the room.

In both briefings, it is important to underline two key points: (1) no sound samples will be recorded since the sensors only register the sound level and not the sound samples and (2) the data gathered by the system will not influence the grade of the students. It is crucial to let students know this, since letting the students think they are highly monitored can represent a bias to the experiment. If the students think that their conversations are being recorded or that making noise can harm their final grade, they can reduce the generation of high noise levels for the wrong reason, which highly jeopardizes the experiment. It is also essential to keep the goals of the experiment secretive to prevent another bias in the experiment. The students should be informed that noise is being monitored, but the true motivation for gathering this data - study its impact on productivity - should be masked as a simple gathering of data on noise pollution in work environments. If students know that measuring their productivity is a crucial element for the study's primary goal, they can make extra efforts to improve it, which harms the experiment.

Once the briefing is finished, and the students have no doubts about the experiment, the APDC classes should continue as they usually would.

7.3.1.2 Professors

The professors lecturing the APDC classes should have more precise insights on the experiment, with more details on the specific data being gathered and the experiment goals. Besides all the information given to the students, the professors would know about the main goals of the experiment, since the professors will provide part of the statistics themselves (*e.g.* the grades of the students). They should also receive a tutorial on how to use the Web Application of the smartOffice since they will receive the role of Administrators of said application. Their main goal as Administrators will be to schedule the periods in which they will be inside the smartOffice attending to students doubts or given a lecture to all the groups. As explained previously, the system should know when these moments occur to prevent the misinterpretation of gathered data.

7.4 Simulation of Hypothetical Scenarios

In this section, we present our simulations on some aspects of the experiment. By observing data gathered by other researchers in their works and cross-referencing it with pre-acquired knowledge on our study case, we were able to simulate possible scenarios regarding the average noise level and the occupancy rate of the smartOffice room and the control room.

7.4.1 Average Noise Level

To try and simulate the behaviour of our control group, we analyzed data presented in studies performed in similar environments. In their study on Noise effect on comfort in open-space offices [37], Pierrette *et al.* measured the noise levels of three distinct open office environments, concluding the averages to be 56, 50 and 48 dB, with the latter being highly influenced by the noise absorbing material used in the office room.

Steelcase, a Furniture company specialized in office equipment, published an article where they claim that the average noise level of an open space office environment ranges from 60 to 65 dB.[42].

Golmohammadi *et al.* measured the noise levels in a bank in their study on Speech Intelligibility and Noise Annoyance, saying the average noise level in bank offices is 48.2 ± 5.5 dB [12].

Cekan *et al.* considered the average expected noise level to be 58 dB in their simulations on how to reduce excessive noise in offices [6].

Fidêncio *et al.* conducted a study on classroom average noise level, and present values from three different classrooms that range from 66.1 dB to 84.3 dB, 71.1 dB to 96.2 and 67.4 dB to 93.0 dB [11].

By analysing these different works on both the average noise level of classrooms and open space office environments, we can see how noise is a difficult thing to measure. With the variation of equipment and environments, it is not possible to state that the average noise of offices and/or classrooms are between a fixed range of values. For our simulation, we assumed that the noise level in our open space office environment was between 50 and 60 dB, during the working hours ours (from 08:00h to 18:00h). This is because of the similarities of our test scenario with the first office of the study of Pierrette *et al.*, with an average noise level of 56 dB. The variance of ±5 dB also seemed reasonable for our work.

An equally important thing to understand is that, based on knowledge from the previous years in APDC, we know that the occupancy rate and the stress level of the occupants of our test environment rise when reaching each of the three delivery dates for their projects. Both these factors (occupancy rate and stress level) have a direct impact on noise level since more people (noise sources) inside the same space usually means an increase in average noise level, and with the stress and pressure of reaching the delivery date, students tend to spend more hours in the room and talk more between them. We are assuming this for our simulation since it was what we observed in the later editions of the APDC class. To represent this increase, we will consider that the average noise level moves from 55 dB to 65 dB over the course of one delivery cycle.

That being said, we considered the function that gives the average noise level over each 30-day delivery cycle the following:

$$y = \begin{cases} -5\cos(\frac{x}{3\pi}) + 60 & 0 < x \leq 30 \\ 5\cos(\frac{x}{3\pi}) + 60 & 30 < x \leq 60 \\ -5\cos(\frac{x}{3\pi}) + 60 & 60 < x \leq 90 \end{cases}$$

Figure 7.1 shows the graph for this function, with every delivery cycle identified with a different colour.

Assuming this function as the base for our simulation, we then used a function to introduce statistical noise over the previous one. This statistical noise adds some controlled randomness to the data, giving them more validity by being closer to what we would gather in a real office. For each day, we compute five random numbers between -5 and 5. Then, we calculate the mean of the five random numbers generated and add it to the corresponding value of the function from Figure 7.1. The result of this addition of noise is shown in Figure 7.2. Each dot represents the simulated average noise level, resultant of the function present previously and the addition of the random number, with the colours representing the three delivery cycles of 30 days each. The red dotted line represents the trend line of the values and is calculated using a polynomial fit with degree 12. This line allows us to see the overall variation of the average noise level.

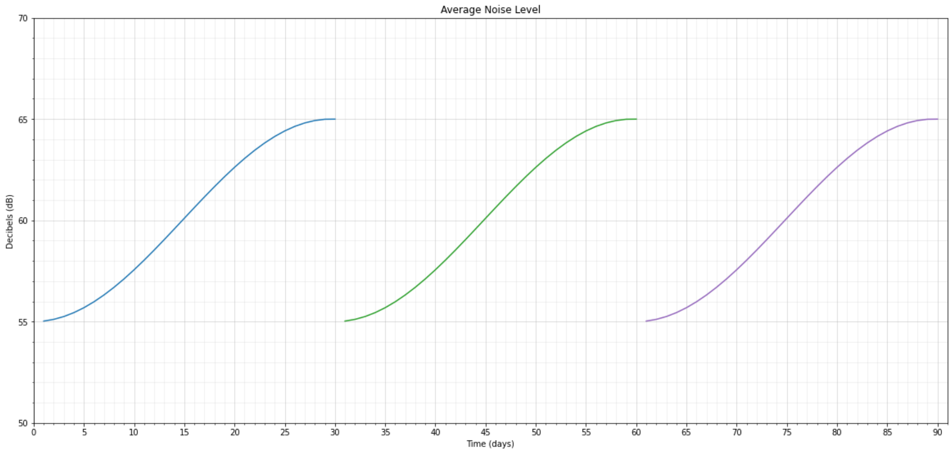

Figure 7.1: Function used on average noise level estimation.

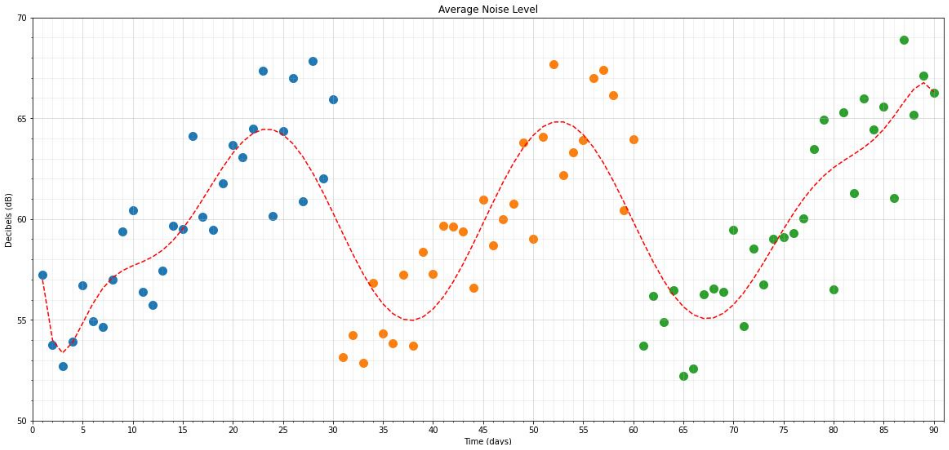

Figure 7.2: Simulation of average noise level

The data in Figure 7.2represents a simulation of the data gathered in the room of the control group. In order to simulate the data of the smartOffice, we need to first generalize the function used to make this simulations. The generalized function is as follows,

$$y = \begin{cases} -\beta\cos(\frac{x}{3\pi}) + \alpha & 0 < x \leq 30 \\ \beta\cos(\frac{x}{3\pi}) + \alpha & 30 < x \leq 60 \\ -\beta\cos(\frac{x}{3\pi}) + \alpha & 60 < x \leq 90 \end{cases}$$

with α representing the mean of the noise level values and β representing the variability of the data from the beginning of the delivery cycle to the end. In the control group, since we wanted to simulate values between 55 dB and 65 dB, $\alpha = 60$ and $\beta = 5$. To this function is then added the statistical noise to add the controlled randomness. With this in mind, we will now present the result of the three possible outcomes, comparing the trend lines of the newly simulated graphs with the control group.

7.4.1.1 Pessimistic Outcome

The pessimistic outcome for this scenario would be for the implemented CPS to have a negative impact on the generated noise levels. In this scenario, we would see values of average noise level from the smartOffice to range between 55 to 70 dB, which means that $\alpha = 62{,}5$ and $\beta = 7{,}5$.

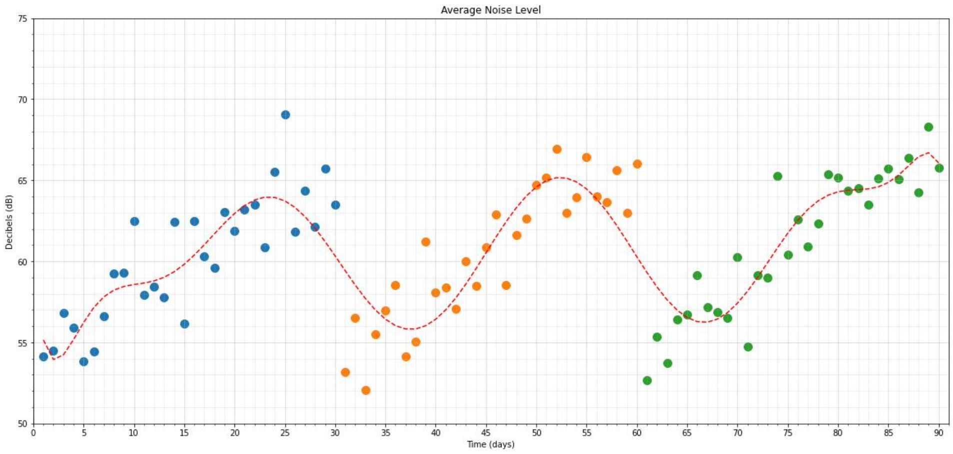

Figure 7.3: Pessimistic simulation of control room average noise level

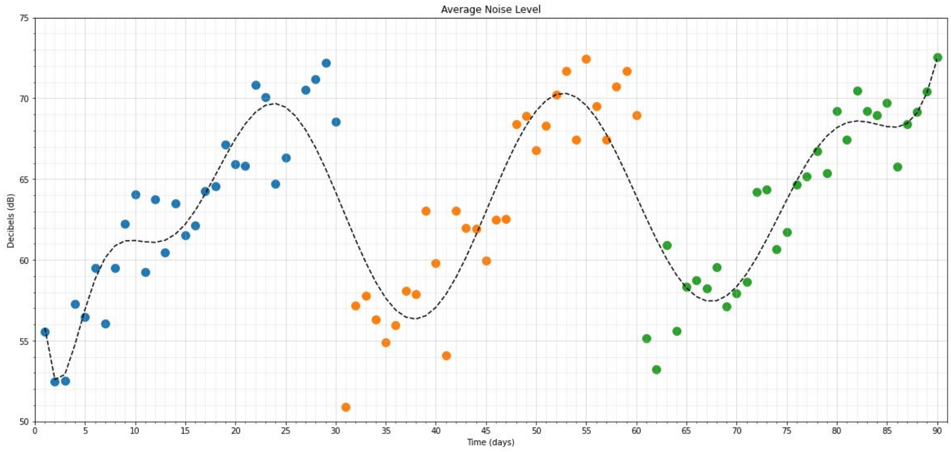

Figure 7.4: Pessimistic simulation of smartOffice average noise level

Figure 7.3 shows the simulated data for the control room (α=60 and β=5), with the dots representing the average noise level of each day, the dot colours identifying the three delivery cycles, and the red line representing the trend line for the average noise level over the experiment.

Figure 7.4 shows the simulated data for the smartOffice (α=62.5 and β=7.5), with the dots representing the average noise level of each day, the dot colours identifying the three delivery cycles, and the black line representing the trend line for the average noise level over the experiment.

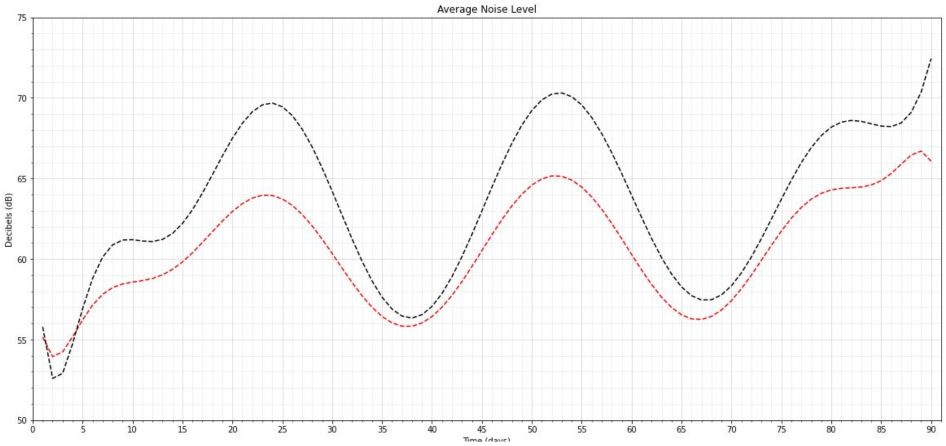

Figure 7.5: Comparison between trend lines of control (red) and smartOffice's (black) average noise levels pessimistically simulated

Figure 7.5 shows a graph comparing side by side both the trend lines from Figures 7.3 (red line) and 7.4 (black line).

By analyzing this data and comparing the two lines of Figure 7.5, we can identify that the data gathered in the smartOffice shows not only an overall higher average noise level but also greater spikes of average noise level when the end of a delivery cycle approaches.

As a reference for future works, data similar to this support that the tested system had a negative impact on the occupants of the room when compared to an environment where there was no CPS trying to reduce it.

7.4.1.2 Neutral Outcome

The neutral outcome for this scenario would be for the implemented CPS to have no impact on the generated noise levels. In this scenario, we would see values of average noise level from the smartOffice similar to those of the control room, ranging between 55 and 65 dB, which means that $\alpha = 60$ and $\beta = 5$.

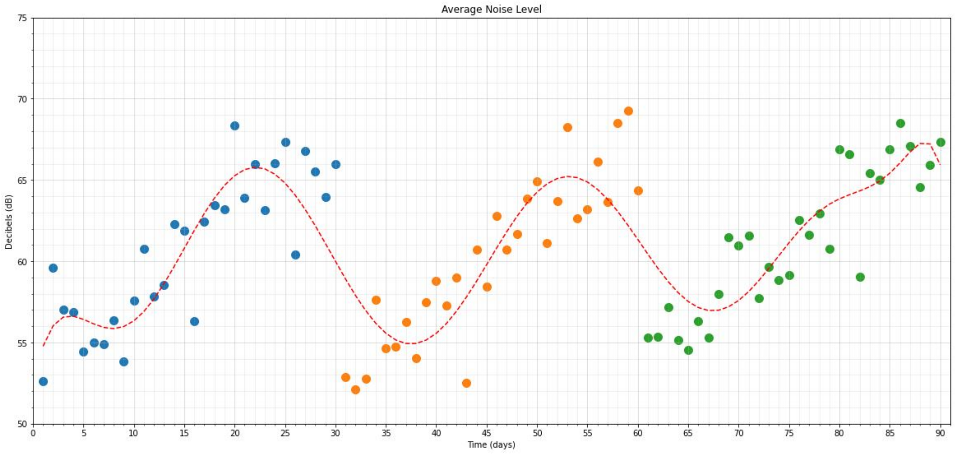

Figure 7.6: Neutral simulation of control room average noise level

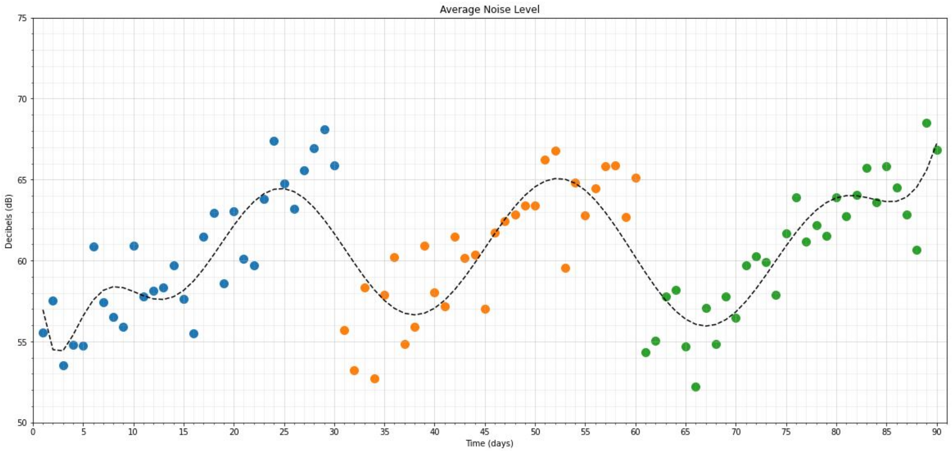

Figure 7.7: Neutral simulation of smartOffice average noise level

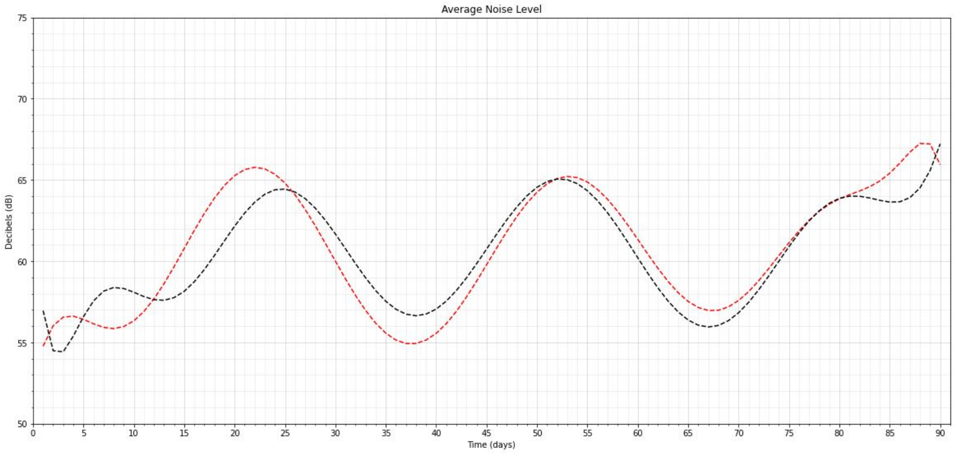

Figure 7.8: Comparison between trend lines of control (red) and smartOffice's (black) average noise levels neutrally simulated

Figure 7.3 shows the simulated data for the control room (α=60 and β=5), with the dots representing the average noise level of each day, the dot colours identifying the three delivery cycles, and the red line representing the trend line for the average noise level over the experiment.

Figure 7.7 shows the simulated data for the smartOffice (α=60 and β=5), with the dots representing the average noise level of each day, the dot colours identifying the three delivery cycles, and the black line representing the trend line for the average noise level over the experiment.

Figure 7.5 shows a graph comparing side by side both the trend lines from Figures 7.3 (red line) and 7.7 (black line).

By analyzing this data and comparing the two lines of Figure 7.5, we can identify that the data gathered in the smartOffice is similar to the data from the control room, showing equivalent values and variations of the average noise level.

As a reference for future works, data similar to this support that the tested system had no significant impact on reducing the noise levels of the room when compared to an environment where there was no CPS trying to reduce it.

7.4.1.3 Optimistic Outcome

The optimistic outcome for this scenario would be for the implemented CPS to have a positive impact on the generated noise levels. In this scenario, we would see values of average noise level from the smartOffice to range between 55 to 60 dB, which means that $\alpha = 57.5$ and $\beta = 2.5$.

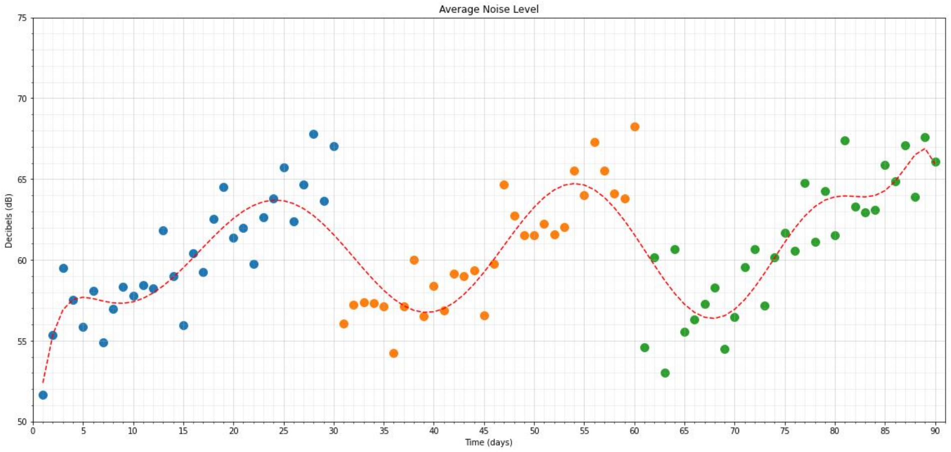

Figure 7.9: Optimistic simulation of control room average noise level

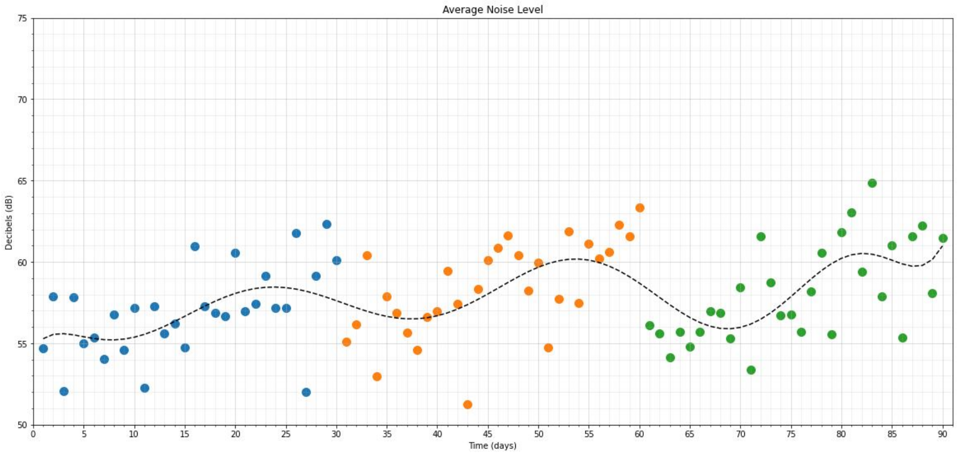

Figure 7.10: Optimistic simulation of smartOffice average noise level

Figure 7.9 shows the simulated data for the control room (α=60 and β=5), with the dots representing the average noise level of each day, the dot colours identifying the three delivery cycles, and the red line representing the trend line for the average noise level over the experiment.

Figure 7.10 shows the simulated data for the smartOffice (α=57.5 and β=2.5), with the dots representing the average noise level of each day, the dot colours identifying the

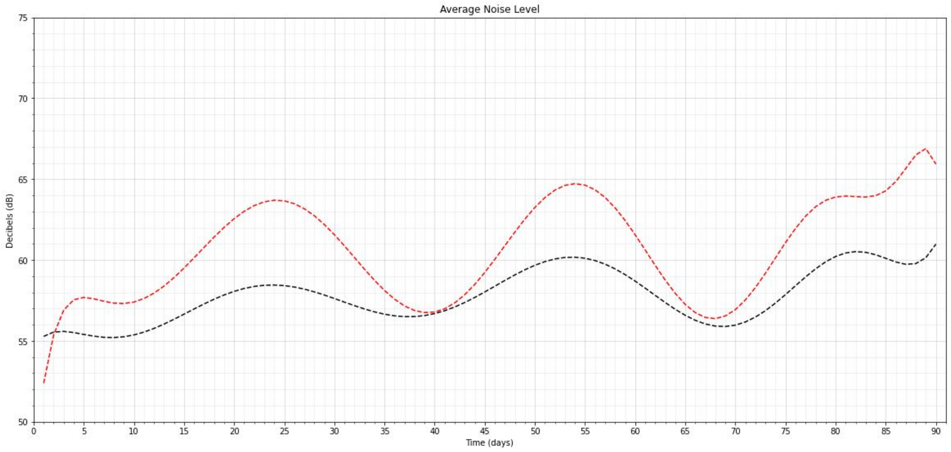

Figure 7.11: Comparison between trend lines of control (red) and smartOffice's (black) average noise levels optimistically simulated

three delivery cycles, and the black line representing the trend line for the average noise level over the experiment.

Figure 7.11 shows a graph comparing side by side both the trend lines from Figures 7.9 (red line) and 7.10 (black line).

By analyzing this data and comparing the two lines of Figure 7.11, we can identify that the data gathered in the smartOffice shows not only an overall lower average noise level but also smaller spikes of average noise level when the end of a delivery cycle approaches.

As a reference for future works, data similar to this support that the tested system had a positive impact on the occupants of the room when compared to an environment where there was no CPS trying to reduce it, reducing the average noise level.

7.4.2 Occupancy Rate

From the questionnaire responses gathered from students of previous APDC editions, we can identify two important statistics: (1) there is a tendency for students to sometimes prefer to work in other places, even if they work inside the APDC rooms regularly (Figure 7.12), and (2) students have a "bellow average"opinion on the noise level conditions inside the APDC rooms, as we analyzed in Section 7.5.2. We will assume that these two concepts are correlated, which can be worded as: "The presence of high noise levels in the APDC work environment triggers some students to choose quieter workspaces to improve their performance and productivity".

Using the data from Figure 7.27, gathered from the works of Meng *et al.* [32] and Dong *et al.* [10], we can estimate that the daily average occupancy rate of an office, during working hours, is around 60%. This is the average occupancy rate between 7:00h and 20:00h which, as we already mentioned, are not very realistic hours for students to work in the APDC room. However, what we are trying to measure here is not the occupancy rate during this time interval, but the occupancy rate of the rooms during the time it has students inside, working, which can vary daily and still would not tamper with the validity of this data.

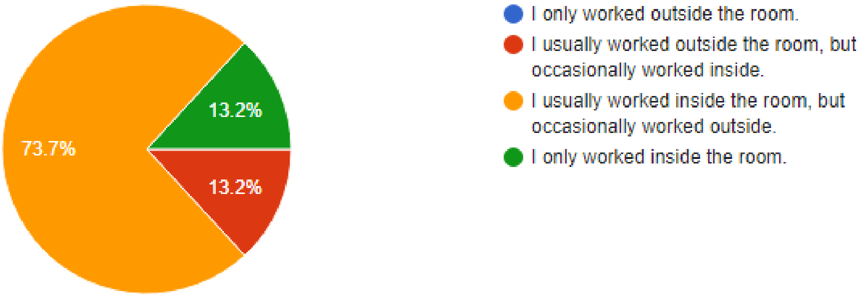

Figure 7.12: Questionnaire answers to "How often did you work inside the APDC room for the project development?"

We also know that similar to the noise level, the occupancy rate of the APDC rooms is lower than the expected values at the beginning of a delivery cycle and tends to increase above average when approaching the end of the delivery cycles. We can hypothesize that this is due to bad planning or low productivity during the early days of the cycle, which demand extra hours of work in the end. With this in mind, we tried to formulate a simulation function to estimate possible outcomes of this analysis, similar to what we did for noise levels.

The function used is the same we used before, since the behaviour is similar to the noise level variations, with the average occupancy rate of each day being given by:

$$y = \begin{cases} -\beta_1 \cos(\frac{x}{3\pi}) + \alpha_1 & 0 < x \leq 30 \\ \beta_2 \cos(\frac{x}{3\pi}) + \alpha_2 & 30 < x \leq 60 \\ -\beta_3 \cos(\frac{x}{3\pi}) + \alpha_3 & 60 < x \leq 90 \end{cases}$$

, with α corresponding to the average occupancy rate of each the delivery cycle, β the largest deviation from the average value a day could have (without the addition of the statistical noise) and θ being the randomizer element. The three different αs and βs correspond to the three different cycles of delivery. For the estimation of the occupancy rate of our control group, we used $\alpha_1 = 60$, $\alpha_2 = 60$ and $\alpha_3 = 60$, since it was the value we calculated from the works of Meng *et al.* [32] and Dong *et al.* [10], and $\beta_1 = 5$, $\beta_2 = 5$ and $\beta_3 = 5$ to compensate for the observable low occupancy rate in the beginning of a cycle and high occupancy rate near the end of it. These α and β values contemplate that the occupancy rate follows the same pattern in all three delivery cycles, thus $\alpha_1 = \alpha_2 = \alpha_3$ and $\beta_1 = \beta_2 = \beta_3$.

This means that the function used to simulate data for the control room was

$$y = \begin{cases} -5\cos(\frac{x}{3\pi}) + 60 & 0 < x \leq 30 \\ 5\cos(\frac{x}{3\pi}) + 60 & 30 < x \leq 60 \\ -5\cos(\frac{x}{3\pi}) + 60 & 60 < x \leq 90 \end{cases}$$

and its results are displayed in Figure 7.13.

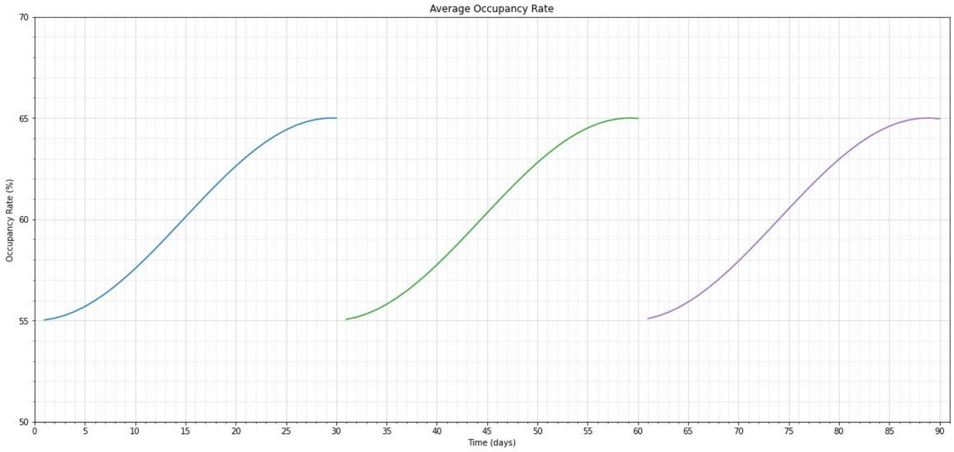

Figure 7.13: Function used on average occupancy rate estimation

To results from this function, we then used a function to introduce statistical noise over the previous one. This statistical noise adds some controlled randomness to the data, giving them more validity by being closer to what we would gather in a real office. For each day, we compute five random numbers between -5 and 5. Then, we calculate the mean of the five random numbers generated and add it to the corresponding value of the function from Figure 7.13. The result of this addition of noise is shown in Figure 7.14. The figure shows one of the simulations of the occupancy rate for the control room, with each dot representing the simulated average noise level, resultant of the function presented previously and the addition of the random number, with the colours representing the three delivery cycles of 30 days each. The red dotted line represents the trend line of the values and is calculated using a polynomial fit with degree 12. This line allows us to see the overall variation of the average noise level.

With this in mind, we conceptualized three scenarios to which we will present the simulated data resultant of this function with other values for α and θ.

7.4.2.1 Pessimistic Outcome

The pessimistic outcome for this scenario would be for the implemented CPS to have a negative impact on the occupancy rate of the room. In this scenario, we would see the values of the average occupancy rate to follow the same pattern, but with significant reductions of values from cycle to cycle. After the bad work environment experienced during the first delivery cycle, we would see people choosing other places to work on the other delivery cycles.

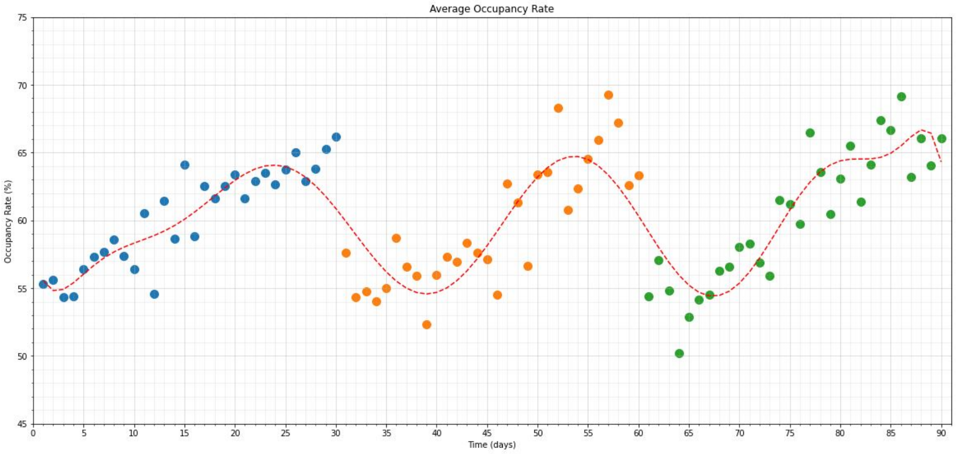

Figure 7.14: Simulation of average occupancy rate for the control room

Figure 7.21 shows the simulated data for the control room ($\alpha_1 = \alpha_2 = \alpha_3 = 60$ and $\beta_1 = \beta_2 = \beta_3 = 5$), with the dots representing the average occupancy rate of each day, the dot colours identifying the three delivery cycles, and the red line representing the trend line for the average occupancy rate over the experiment.

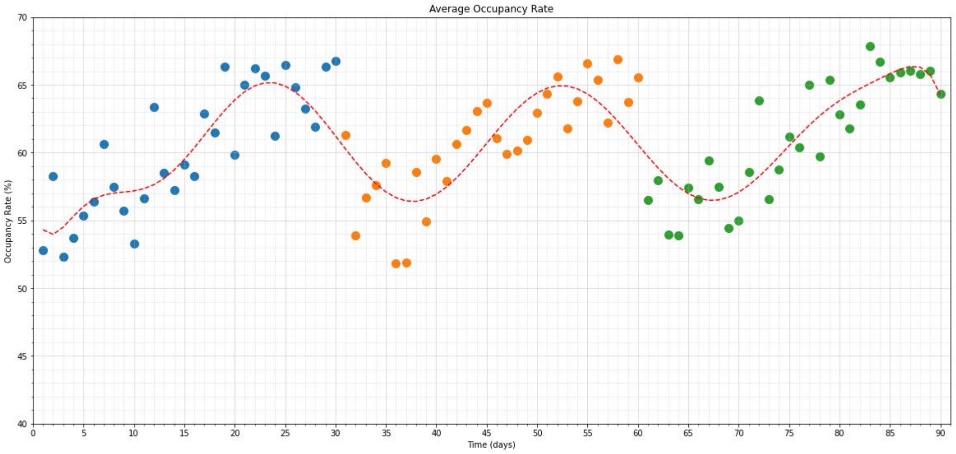

Figure 7.15: Pessimistic simulation of average occupancy rate for the control room

Figure 7.22 shows the simulated data for the smartOffice ($\alpha_1 = 60$, $\alpha_2 = 55$, $\alpha_3 = 50$ and $\beta_1 = \beta_2 = \beta_3 = 5$), with the dots representing the average occupancy rate of each day, the dot colours identifying the three delivery cycles, and the black line representing the trend line for the average occupancy rate over the experiment.

Figure 7.23 shows a graph comparing side by side both the trend lines from Figures 7.21 (red line) and 7.22 (black line). By analyzing this data and comparing the two lines of Figure 7.23, we can identify that the data gathered in the smartOffice shows not only an overall lower average occupancy rate but also a decrease in average occupancy rate from one delivery cycle to the next.

As a reference for future works, data similar to this support that the tested system could have a negative impact on the office room work conditions, namely regarding noise

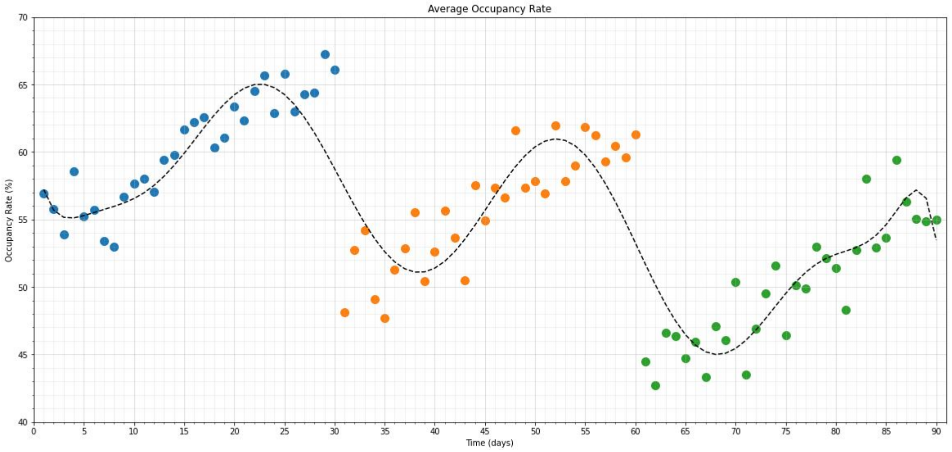

Figure 7.16: Pessimistic simulation of average occupancy rate for the smartOffice

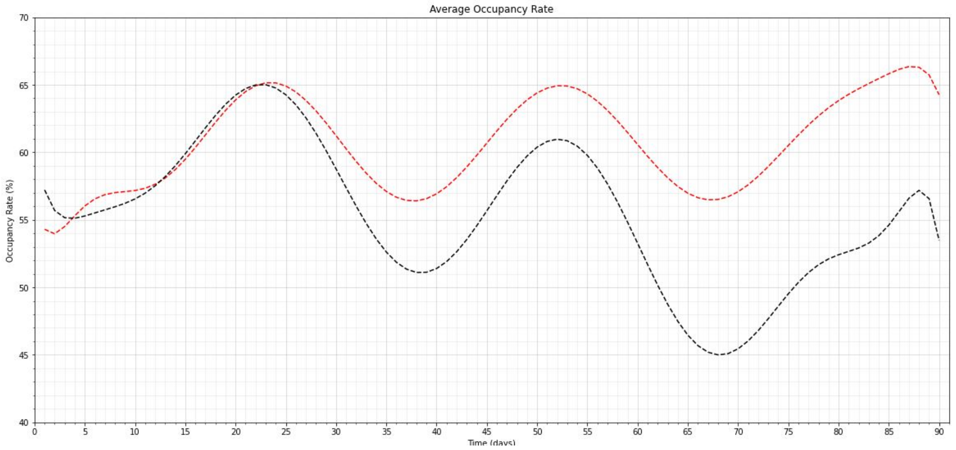

Figure 7.17: Comparison between trend lines of control (red) and smartOffice's (black) average occupancy rates pessimistically simulated

levels when compared to the control room, where no CPS was trying to reduce it.

7.4.2.2 Neutral Outcome

The neutral outcome for this scenario would be for the implemented CPS to have a non-significant impact on the occupancy rate of the room. In this scenario, we would see the values of the average occupancy rate to follow the same pattern, with no significant changes of values from cycle to cycle.

Figure 7.18 shows the simulated data for the control room ($\alpha_1 = \alpha_2 = \alpha_3 = 60$ and $\beta_1 = \beta_2 = \beta_3 = 5$), with the dots representing the average occupancy rate of each day, the dot colours identifying the three delivery cycles, and the red line representing the trend line for the average occupancy rate over the experiment.

Figure 7.19 shows the simulated data for the smartOffice ($\alpha_1 = \alpha_2 = \alpha_3 = 60$ and $\beta_1 = \beta_2 = \beta_3 = 5$), with the dots representing the average occupancy rate of each day, the dot colours identifying the three delivery cycles, and the black line representing the trend

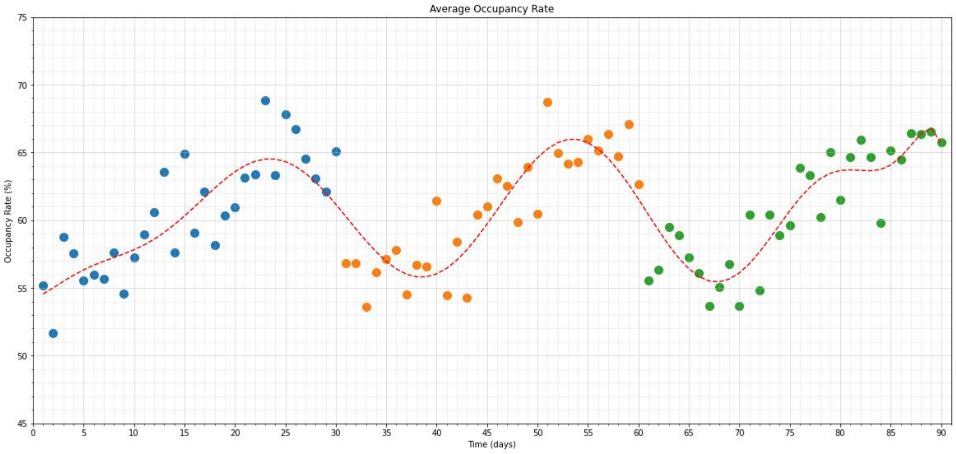

Figure 7.18: Neutral simulation of average occupancy rate for the control room

line for the average occupancy rate over the experiment.

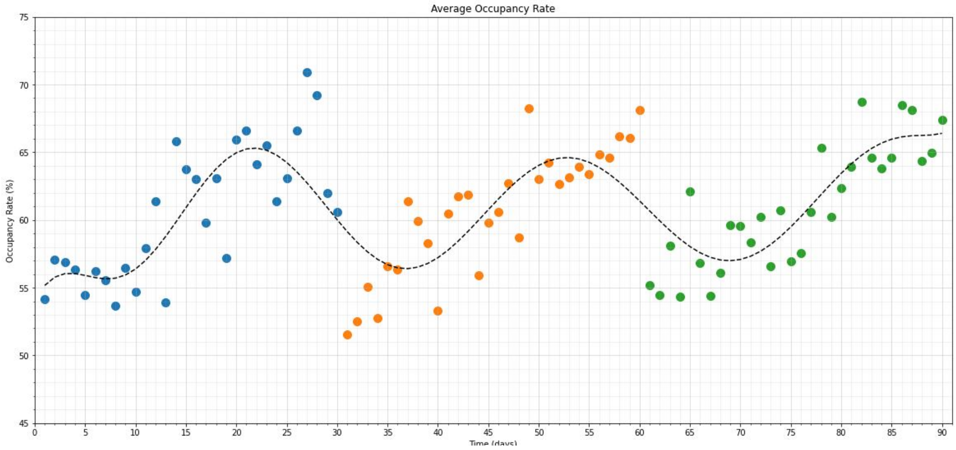

Figure 7.19: Neutral simulation of average occupancy rate for the smartOffice

Figure 7.20 shows a graph comparing side by side both the trend lines from Figures 7.18 (red line) and 7.19 (black line). By analyzing this data and comparing the two lines of Figure 7.20, we can see how the two lines are close to each other for the duration of the experiment, which shows how the occupancy rate of both the smartOffice and the control room are equivalent.

As a reference for future works, data similar to this support that the tested system had no particular impact on the office occupancy rate.

7.4.2.3 Optimistic Outcome

The optimistic outcome for this scenario would be for the implemented CPS to have a positive impact on the occupancy rate of the room. In this scenario, we would see the values of the average occupancy rate to follow the same pattern, but with significant increases of values from cycle to cycle. After the good work environment experienced

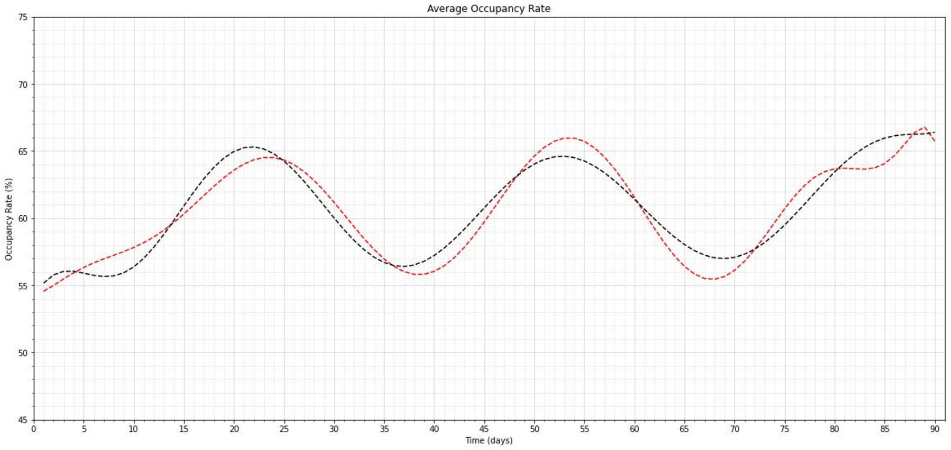

Figure 7.20: Comparison between trend lines of control (red) and smartOffice's (black) average occupancy rates neutrally simulated

during the first delivery cycle, we would see people choosing to work in the smartOffice with each delivery cycle.

Figure 7.21 shows the simulated data for the control room ($\alpha_1 = \alpha_2 = \alpha_3 = 60$ and $\beta_1 = \beta_2 = \beta_3 = 5$), with the dots representing the average occupancy rate of each day, the dot colours identifying the three delivery cycles, and the red line representing the trend line for the average occupancy rate over the experiment.

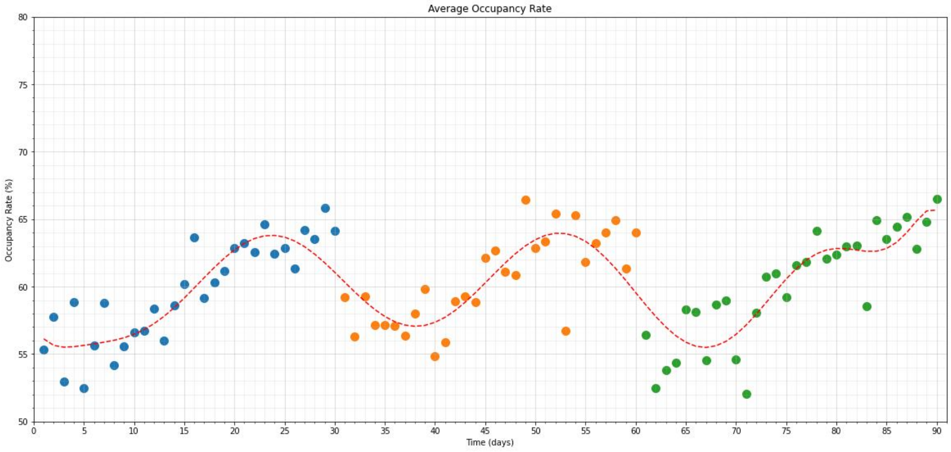

Figure 7.21: Optimistic simulation of average occupancy rate for the control room

Figure 7.22 shows the simulated data for the smartOffice ($\alpha_1 = 60$, $\alpha_2 = \alpha_3 = 65$ and $\beta_1 = 5$, $\beta_2 = \beta_3 = 2$), with the dots representing the average occupancy rate of each day, the dot colours identifying the three delivery cycles, and the black line representing the trend line for the average occupancy rate over the experiment.

Figure 7.23 shows a graph comparing side by side both the trend lines from Figures 7.21 (red line) and 7.22 (black line). By analyzing this data and comparing the two lines of Figure 7.23, we can identify that the data gathered in the smartOffice shows not only an overall higher average occupancy rate but also a small increase in average occupancy

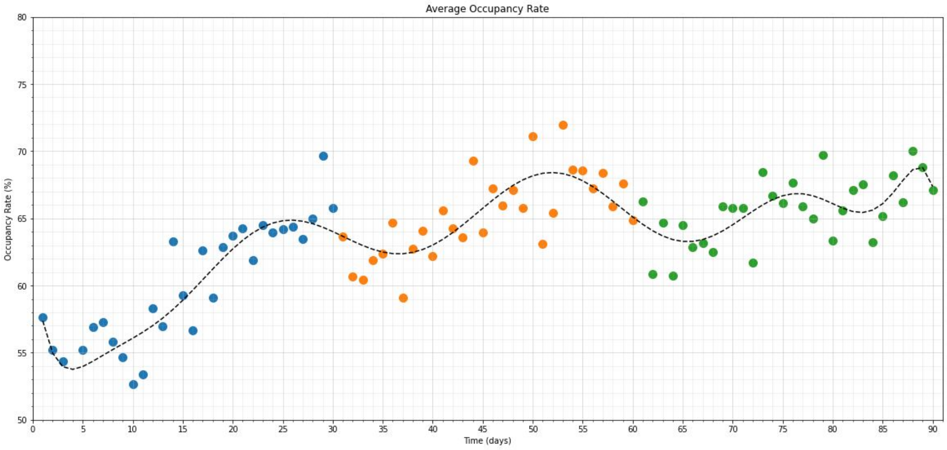

Figure 7.22: Optimistic simulation of average occupancy rate for the smartOffice

rate from the first delivery cycle to the others.

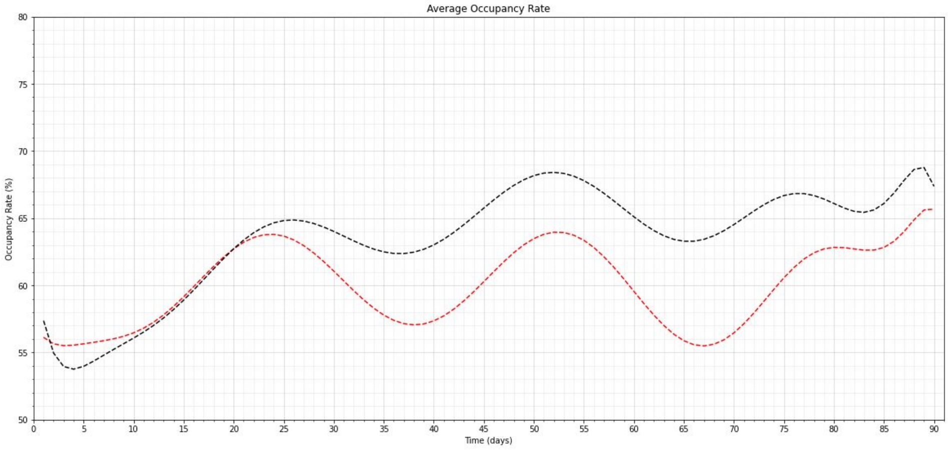

Figure 7.23: Comparison between trend lines of control (red) and smartOffice's (black) average occupancy rates optimistically simulated

As a reference for future works, data similar to this would support that the tested system could have a positive impact on the office room work conditions, namely regarding noise levels when compared to the control room, where no CPS was trying to reduce it.

7.4.3 Simulation as an experiment preparation

The simulation we presented in this section has small validity when it comes to drawing conclusions from them since they are done using generated data and under hypothetical scenarios.

That being said, they have a key role in our work, helping us to design the experimental guidelines based on some data (even if it is generated data), and for future works using our case study, by providing a starting point regarding the expectations of possible scenarios for the APDC class. Since we assume what to expect from both the average noise level and the occupancy rate during the experiment, we can conceptualize how we will analyze the data, once it is gathered during the experiment, to answer our research questions.

Even if the data gathered upon the realization of the experiment proves that none of the hypothetical scenarios for which we present simulations are real, the presented simulations can help us to understand how to interpret the real results.

7.5 Experimental and Analytical Guidelines

The focus of these experimental guidelines is to propose analytical methods to interpret the data gathered in the context of our study case. Only by performing this experiment, we will have a true valid answer on how effective is our system in lowering the noise level of the room, improving the productivity of its occupants and other research questions, as we will present in this section. These guidelines can also give some insight on how to interpret data gathered in future experiments using our system.

7.5.1 Is the implemented CPS able to reduce noise?

The simulated data we showed in section 7.4.1 hints at the various possible scenarios of average noise level variation over the duration of the experiment. In order to answer this question, the researchers must do some specific comparisons. Since the dimensions and possibly the number of occupants of the smartOffice and the control might not be the same, a simple direct comparison between values of average noise levels from both rooms might be deceiving. One of the rooms might show an average noise level higher than the other simply due to having more occupants in a smaller sized room.

Nevertheless, the comparison of values as we did in the simulations of section 7.4.1 still present a valid metric to analyze the system's capacity on lowering the growth of the average noise level values when approaching the end of a delivery cycle. This can be observed by observing the trend lines of the data from both rooms.

A better way to find an answer to the question would be to first establish the expected average noise level of each room, by performing some sample measurement in the early days of the experiment and analyze the data with these expected values in mind. We can hypothesize a scenario where the smartOffice, even with higher average noise level values than the control room, still shows significantly lower values when compared to the expected average, which can be interpreted as a sign of its capacity to reduce noise.

Another way to analyze the efficiency of the system in reducing the noise level is to compare the amount of time each room spends with disruptive noise levels. This can be measured by analyzing the time each room stays above a defined threshold. If we can observe that in the smartOffice, the occupants tend to go back to normal noise levels quicker, we can assume it is due to the intervention of the system's actuators, thus assessing its efficiency in lowering noise.

7.5.2 Do the smartOffice occupants enjoy the office work conditions and the implemented CPS?

In this scenario, we aim to analyze the occupants' overall satisfaction with the room where they are working. The occupants from both the control room and the smartOffice should answer a series of questionnaires during the experiment about their comfort and work conditions. One for each delivery cycle. From these questionnaires, we will be able to retrieve data on how the occupants from both rooms perceive their work environment, particularly about noise levels, and compare results from both rooms.

Figure 7.24 shows the data gathered through questionnaires answered by students of previous editions of the APDC course. This data was not simulated.

Figure 7.24: Opinions on noise level from previous editions of APDC

From this data, we can observe that from a sample of 38 responses, only 36% of the students revealed to be "Satisfied"with the noise level condition of the office room, and 0 students answer with "Very satisfied". 31% of the answer pointed at being indifferent to the noise level, while 21% responded with "Dissatisfied"and 10% with "Very dissatisfied".

The possible answers to the questionnaire are, in fact, five Likert items of a Likert scale. The occupants of both rooms should answer the same question as we asked the student from other editions of APDC: "How satisfied are you with the noise levels on your assigned workspace?", to which they can answer one of five options: "Very dissatisfied", "Dissatisfied", "Indifferent", "Satisfied"or "Very satisfied", with their respective value from 1 to 5 on the Likert scale. We can then calculate the mean value of all the responses to the questionnaire, which we will refer to as the Noise Level Average Satisfaction (NLAS) by adding the numeric value of each response, and then dividing by the number of respondents, using the following formula:

$$NLAS = \frac{1 \times \alpha_1 + 2 \times \alpha_2 + 3 \times \alpha_3 + 4 \times \alpha_4 + 5 \times \alpha_5}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5}$$

, where α_1 is the number of "Very dissatisfied"responses, α_2 is the number of "Dissatisfied"responses, α_3 is the number of "Indifferent"responses, α_4 is the number of "Satisfied"responses and α_5 is the number of "Very satisfied"responses.

With this in mind, we can now calculate the NLAS for the data shown in Figure 7.24:

$$NLAS = \frac{1 \times 4 + 2 \times 8 + 3 \times 12 + 4 \times 14 + 5 \times 0}{38} \approx 2.95$$

This means that, on a Likert scale with 5 items, the open space office environment provided by the previous editions of APDC scored a Noise Level Average Satisfaction of approximately 2.95. This data can be useful if we wish to compare the data gathered in previous editions of APDC with the data gathered during the realization of the experiment, as we will explain.

After gathering the data of both the control and the smartOffice room, via questionnaire responses, the researchers should perform a statistical test to assess if the data from both rooms shows significant differences between them. Methods like the Independent Samples T Test [45], the Mann Whitney U Test [41] or the Welch T Test [2] are all designed with the goal of proving with some degree of certainty that the statistical distributions of two groups are significantly different or not. We propose that, after the data gathering, the test that best suits the data should be chosen by the researchers, and they should apply them to find out if the statistical distribution of both room's responses is different.

If the difference is proven by the statistical test, the researchers should then calculate the effect size of the population, which is done by dividing the two population mean difference by their standard deviation.

By using the statistical test best suitable for the data, it is possible to conclude if the two groups of data have or do not have a significant difference of distributions. If the difference is proven, the effect size will show the difference between the means of each group and, in turn, which room had the better responses to the questionnaire.

7.5.3 Does the implemented noise-controlling CPS improve productivity?

As explained in chapter 3, there are many theories about which is the best method to assess productivity levels in a work environment.

To answer this question, we propose the usage of the perceived productivity, a method more subjective but sometimes fairer, the assessment of productivity through the value of the final product, a more objective method, but that can sometimes be deceiving, since we are talking about projects that involve multiple workers, and the assessment of productivity through the analysis of the occupancy rate of the office room during certain hours of the day.

7.5.3.1 Perceived Productivity

To assess perceived productivity, the occupants from both rooms should answer questionnaires about how they evaluate their productivity levels. These questionnaires will provide a comparison between how the occupants of the different rooms see their productivity short and mid-term.

The occupants should respond to the questionnaire in Appendix B, answering the question "How would you evaluate your amount of completed work, when compared to your expectations at the beginning of the week"with one of five options: "This week was really bad productivity-wise. I did less than half the work I expected.", "This week was bad productivity-wise. I did more than half, but still less work than I expected.", "This week was satisfactory productivity-wise. I did all the work I expected.", "This week was good productivity-wise. I did more than the work I expected."or "This week was really good productivity-wise. I did almost double the work I expected.".

Similar to the last section, this is a Likert scale with five items, and the same guidelines apply here. First, a statistical test like the Independent Samples T Test [45], the Mann Whitney U Test [41] or the Welch T Test [2] must be chosen according to the features of the gathered data. If the statistical test result indicates that the difference between the statistical distribution of the perceived productivity between occupants of the smartOffice and the control room is significant, the researchers should calculate the effect size of the population, which is done by dividing the two population mean difference by their standard deviation.

This questionnaire must be answered at least once every delivery cycle, but to increase the precision of the data, it can be done at the end of every week. The analytical process is the same for every time the questionnaire is done.

7.5.3.2 Product value (APDC grades)

To estimate productivity through the final grade of their projects, we propose the calculation of the average of the grades of both the smartOffice and the control room, as well as the average of grades from previous editions of APDC. It is difficult to correlate one excellent grade with our CPS's efficiency but if the average of grades of the room is significantly higher, that correlation gains strength, since the probability of it being a brilliant student that would have a great grade despite the environment is lower.

However, some facts must be taken into consideration: between editions of APDC, students change, projects change and the teaching team may change. These variables can introduce some unaccounted factors that can contribute to the normalization of the grades, *e.g.* if the project is harder than the previous editions, the professors might consider giving a compensation to all grades in order to keep justice among students' grades from different years, to prevent that students who got a harder project to get their grades unfairly harmed by the extra difficulty of the project.

In Figure 7.25, we present the grades form the APDC editions of the academic years of 2020/2021 (blue), 2019/2020 (orange) and 2018/2019 (grey). From this data, we must calculate the average grade of each year, by adding the product of the grades by its respective percentage and dividing the result of the additions by 100. For simplicity of the data, the grades below 9 are clustered in that value, since there were no records of students scoring 9 or lower in the data. The results are as follows:

$$AvgGrade_{20/21} = \frac{10\times 0+11\times 0+12\times 0+13\times 0+14\times 7.35+15\times 14.71+16\times 25+17\times 30.88+18\times 17.65+19\times 4.41+20\times 0}{100} = 16.5$$

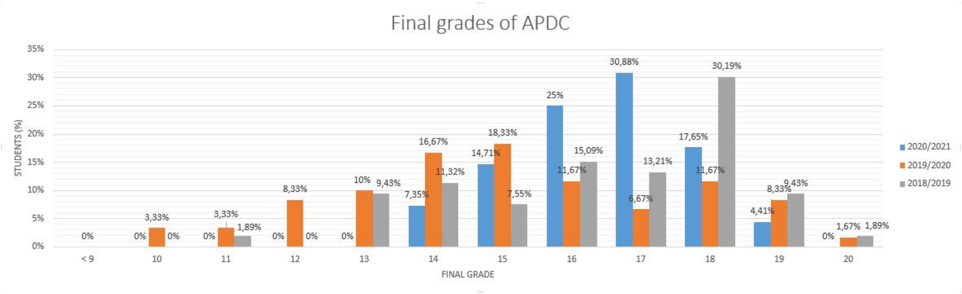

Figure 7.25: Grades from previous editions of APDC, in percentage

$$AvgGrade_{19/20} = \frac{10\times3.33+11\times3.33+12\times8.33+13\times10+14\times16.67+15\times18.33+16\times11.67+17\times6.67+18\times11.67+19\times8.33+20\times1.67}{100} = 15.1006$$

$$AvgGrade_{18/19} = \frac{10\times0+11\times1.89+12\times0+13\times9.43+14\times11.32+15\times7.55+16\times15.09+17\times13.21+18\times30.19+19\times9.43+20\times1.89}{100} = 16.4151$$

To make it easier to compare with the data gathered from the smartOffice and control room, we can calculate the average grades from all the previous editions of APDC in one data set. Figure 7.26 shows the graphical representation of this data.

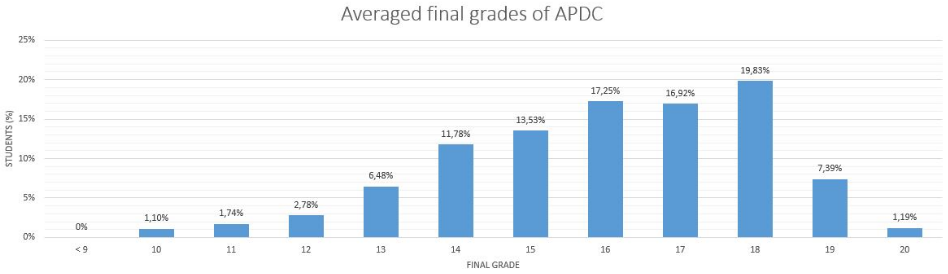

Figure 7.26: Average of grades from previous editions of APDC, in percentage

From this data, we can also calculate the average grade of the averaged grades from the three editions of APDC:

$$AvgGrade_{20/21} = \frac{10\times1.1+11\times1.74+12\times2.78+13\times6.48+14\times11.78+15\times13.53+16\times17.25+17\times16.92+18\times19.83+19\times7.39+20\times1.19}{100} = 16.004$$

As a guideline for future works, we can use this methodology to calculate the average grade for the class of each room, smartOffice and control room, and try to make some conclusions, but the researcher should always keep in mind the limitations of this metric mention previously. A higher average grade can mean that the overall performance of the group was better than the group we are comparing it to, but should not be rashly accepted as a sign that our system caused students to increase their final grades since there can be unaccounted factors tampering with the results.

7.5.3.3 Hours of work

This method consists of analysing data about the occupancy rate of offices and try to estimate productivity based on one concept: "In most of the daytime working schedule office environments, the increase of the occupancy rate before 8 am and after 6 pm can be related to lower levels of productivity during the normal working hours".

As explored by Meng *et al.* in their work on the behaviour of occupants in office buildings [32] and by Dong *et al.* on the impact of occupants' behaviour on energy consumption in office buildings [10], the normal curve of the occupancy rate of an office with a "9 to 5"working schedule is as represented in Figure 7.27

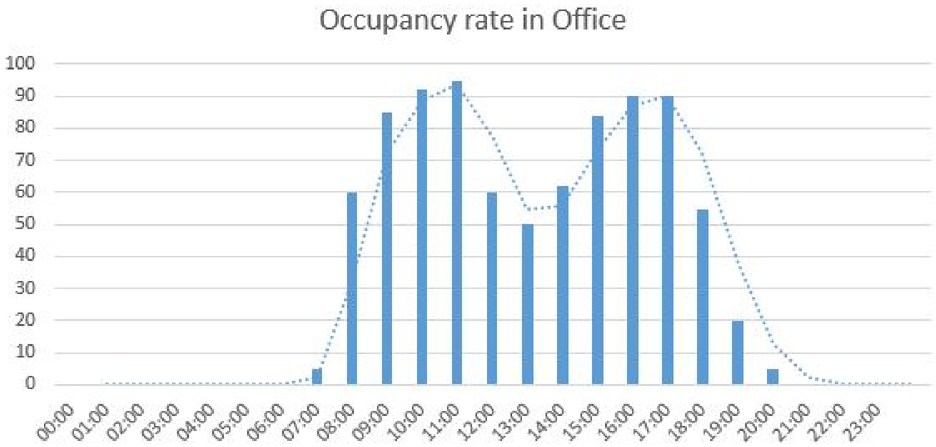

Figure 7.27: Variation in the occupancy rate in office buildings from the questionnaire data and the manual data[32]

The idea behind this concept is that, if the normal working hours are not productive enough, the worker might need to stay in the office extra hours in the evening or arrive earlier the next day to compensate for the low productivity levels of the previous day, which is a plausible scenario. However, we can not assume that every case where a worker stays extra hours in the workplace is a sign of lower productivity during the "normal"working hours. This method should be used only in combination with other methods of measuring productivity to ensure that we are not considering lack of productivity of an element or a team when it does not apply, *e.g.* they are working with a client on a different time zone, thus having to schedule meetings outside the standard working hours.

This method has even greater validity threats when dealing with students, majorly due to their work schedule. It is predictable that, if we gathered this type of data and analyzed it in this way, we would get a different curve. This is because students have more subjects than APDC during the semester, which makes their working hours vary from day to day, and from student to student.

That being said, it is a valid method of assessing productivity in a professional office environment when in combination with others to eliminate false positives of lack of productivity.

7.5.4 Do people prefer to work in the smartOffice?

The occupancy rate can be used as a metric to assess the quality of the work environments. Starting from the concept that good working conditions make workers want to work in that environment, we can assume that if we register high rates of occupancy, it might be related to the provided conditions of work, namely conditions of the noise level.

The simulations presented in section 7.4.2 show hypothetical scenarios that future works should used as a baseline for what to expect from the gathering of occupancy rate data. However, researchers should gathered their data, construct a graph using this data and draw out their own conclusion on the behaviour of the trend lines of their data.

They should also keep in mind that outside our study case, a high occupancy rate can be related to other variables, not cover in the context of our work like the impossibility of the occupant to perform their work outside the studied workplace, for example. The occupancy rate can only be correlated with the preference of the occupant to work in that workplace if they have the choice of working anywhere else.

7.6 Summary

After the analysis of our simulations of hypothetical scenarios for the average noise level and the occupancy rate and the realization of the experiment and analysis of the data gathered over its duration, the researchers will have a grasp on the system true efficiency in reducing the overall noise level of and open space office environment.

In the next chapter, we will approach some limitation to the contexts in which the presented guidelines can be applied as well as some validity threats to the conclusions drawn from the execution of the proposed experiment.

Chapter 8

Discussion of Limitations

In this chapter, we present some discussion points for this dissertation. Section 8.1 approaches some limitations of the context of our work. Section 8.2 presents some statements on the validity of the experiment data and its interpretation.

8.1 Context Limitations

The CPS we created is designed to be a tool for controlling noise levels in a software development multi-team open space office environment. That being said, the system has some limitations. In this section, we will present those limitations, namely on the environmental context in which the system is acting.

8.1.1 Academic Context

We designed the system and the experimental guidelines contained in this dissertation with an academic context as its foundation. However, our context was very restrictive when compared to the general academic context. In a standard course, in which the students attend regular classes and lectures, the noise levels are generally low, with a few exceptions. The lower noise levels can correlate to various factors, like the room layout, the number of students inside the room or the presence of a professor in the room at all times. The usefulness of our system dramatically decreases when we leave the multi-team open space office environment, which the APDC course provides to the attending students.

Nevertheless, the system can be useful in an academic context similar to the APDC course, but outside the context of the Computer Science degree. In every case where we have a class that tries to mimic a multi-team open space office environment, following the same concepts of APDC, can make use of our system to try to improve the occupants' productivity levels by lowering the room noise level.

8.1.2 Professional Context

In the context of a professional multi-team open office environment is where our system has more potential but is also where it is more vulnerable to its flaws.

Since it is common for modern companies to have open space offices with multiple teams working in the same room, most of the assumptions made when designing the system regarding the physical environment are valid. We can not say the same when regarding the behaviour of the occupants of the workspace. As Runeson concluded in his study, the usage of college students to undergo scientific studies can neither be accepted nor rejected as the equivalent of using industry people [39]. On one side, college students can show behaviour that would be acceptable in a professional scenario, as well as equivalent productivity levels to those of professional workers. On the other, professional workers tend not only to have more maturity and responsibility to perform a certain task but also the pressure of losing their job in cases of extremely low productivity.

With this in mind, we can assume that the conclusions retrieved from the analysis of data gathered using our system combined with our simulations and experimental guidelines described in the previous chapter can be applied to some business contexts with a multi-team open-space office, but should not be broadly accepted without further experimentation with other population as experimental subjects.

8.2 Validity of the data

The data present in the previous chapter is endangered by some validity threats that we must keep in mind when using it to draw conclusions for our study.

The main threat to the validity of our data is that we are dealing, in most cases, with simulations and generated data. Even though we used real data, either gathered by us in the last year or by other researchers in their studies, to produce the functions to generate this data, we can not assure that the simulated behaviours would be what we would observe in a real experiment.

For example, in our experiment, we have the smartOffice students and the control room students. We can not predict the effect on the behaviour of the students when confronted with the reality that their rooms have different work conditions. We could have the students of the control room feeling inferior to their colleagues, feeling demotivated and lowering their productivity to value below the ones we predicted during our simulations. The exact opposite can also be true: the students from the control might feel that they can prove to everyone that, even in a room without a noise reduction system, they can be the most productive students in the class, and present productivity levels higher than the values we predicted. This same logic can be applied to all the data that is dependent on human behaviour.

The threats we discussed in this chapter do not invalidate our conclusions or data simulation and analysis guidelines but they are key concepts to keep in mind when using this dissertation for future works.

Chapter 9

Conclusion

This chapter presents the conclusions of this dissertation. Section 9.1 provides a detailed description of the achieved goals and consequent conclusions and Section 9.2 presents suggestions of future works to develop based on this dissertation.

9.1 Conclusion

The goals of designing and implementing our CPS, as described in Chapter 5, and of validating the implementation through integrity tests, addressed in Chapter 6 were achieved. Our system provides a functional tool that aims at improving the office occupants productivity by lowering the noise level inside the multi-team open-space software development office environment. The system can be used in either an academic or professional context of the same environmental nature, although some assumptions on human behaviour must be made for the safekeeping of the data validity, as we addressed in the previous chapter. This dissertation also contains, in Chapter 7, the results of simulations done using data gathered by us in previous years, as well as data gathered by other researchers in the context of their works, in hopes of presenting hypothetical scenarios for the variation of average noise level and occupancy rate close to what we will gather in the real APDC environment during the experiment. In the same chapter, we also provide guidelines for future researchers that want to use our system to perform the study of its efficiency using the APDC study case on how we think the analysis of the gathered data should be done. The implementation of our CPS by itself brings value to the research community. Not only is the system ready for the experiment we designed it to, but it also represents a starting point for future works, even approaching subjects not related to noise reduction, as we will discuss in the next section.

9.2 Future Work

Both the simulations and experimental guidelines, as well as the implemented system, compose what can be a starting point for various future works.

The most obvious future work would be to perform the experiment described in detail in Chapter 7. When the prerequisites are met, such as the possibility of having students in the classrooms, the researchers can install our system using the guidelines provided and perform the mentioned experiment to gather real data from a real environment. Only by analysing data gathered in a real environment, as opposed to simulated data, we will have a true valid answer on how effective is our system in (1) lowering the noise level of the room and (2) improving the productivity of its occupants.

The next set of researches that could use our work as a starting point are studies that aim to replicate the simulated experiment but in a professional environment. For this kind of study, we advise the researchers to follow the experimental guidelines with special attention to the differences between studies involving students or professional works, as we discussed previously.

Our system can also be the subject of improvement by future works, either improving on the mechanisms already designed and implemented, or by adding a new mechanism that may increase the system's performance and efficiency in lowering the noise level and improving productivity. A component that can likely be improved is the Web Application, which we use mostly as a Controller for the implemented CPS. This application that serves the purpose of being (1) a controller of the system from an administrator point of view and (2) an event calendar for the normal users, can suffer significant transformations with the addition of more functionalities. One idea we suggest exploring would be to add Software Engineering functionalities, that would help the users to plan their work for the next weeks and the administrators to monitor the work plan of the users. The addition of data visualisation functionalities could also be of interest, helping administrators on improving the management of the system and its users, and the users on self-monitoring their behaviours.

Our last suggestion for future works would be to extend the implemented CPS to other physical variables. The same data that led us to focus our study and project around noise reduction also points out other problematic physical variables, that pose a threat to productivity in the work environment. Since we designed the system with extensibility and scalability in mind, future works could add other sensors, actuators and controller logic functionalities that focus on controlling other physical variables, such as temperature or light intensity, and support studies on their impact on productivity.

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APPENDIX A

QUESTIONNAIRE 1

Satisfaction with the rooms of APDC - Projecto

This survey aims to collect the opinions of students taking the APDC - Projecto classes about their work environment conditions. It is part of the research work under the context of a Master thesis of Tiago Caldinhas, to look for improvement opportunities by implementing tooling and introducing automation devices for supporting the students in the working environment. The questions will regard the satisfaction with different aspects of the rooms where you have been working on and possible improvements to be implemented. It will not take more than 10 minutes to complete. Be frank and honest in your answers. Your answers will only be used for academic purposes and will be anonymous. The collected data will be used solely for the thesis. Thank you very much for your time and cooperation.

*Required

1. **To what room was your APDC group assigned to?** *

   Mark only one oval.

   ○ Lab 116
   ○ Room 240

2. **Was APDC your first experience working on a "multi-team" office environment?** *

   Mark only one oval.

   ○ No
   ○ Yes

3. **If no, please describe your previous experience(s).**

   ____
   ____
   ____
   ____
   ____

4. **How often did you work inside the APDC room for the project development?** *

Mark only one oval.

○ I only worked outside the room. *After the last question in this section, skip to question 15.*

○ I usually worked outside the room, but occasionally worked inside. *After the last question in this section, skip to question 6.*

○ I usually worked inside the room, but occasionally worked outside. *After the last question in this section, skip to question 6.*

○ I only worked inside the room. *After the last question in this section, skip to question 6.*

5. **Choose the physical feature that you consider the most important in making a workplace pleasant for you to work.** *

Mark only one oval.

○ Comfortable temperature
○ Noise-free environment
○ Adequate luminosity
○ Good ventilation
○ Other: ______________________

APDC Room

These questions are referring to the room and workplace assigned to you in APDC.

6. **How satisfied are you with the following aspects of your assigned workspace?** *

Mark only one oval per row.

	Very dissatisfied	Dissatisfied	Indifferent	Satisfied	Very satisfied
Lighting	○	○	○	○	○
Noise level	○	○	○	○	○
Temperature	○	○	○	○	○
Ventilation	○	○	○	○	○

7. **Do you prefer working in natural light, artificial light, or a combination of both?** *

Mark only one oval.

○ Natural light
○ Artificial light
○ Combination of both

8. **How often did the lighting of the room ever cause reflections in your work material?** *

Mark only one oval.

○ Never
○ Occasionally
○ Sometimes
○ Often
○ Always

9. **Is your workplace near the room windows?** *

Mark only one oval.

○ Yes
○ No

10. **How often did you found the room empty and the lights turned on?** *

Mark only one oval.

○ Never
○ Occasionally
○ Sometimes
○ Often
○ Always

11. **How often does the room temperature become too hot or too cold, when compared with the outside temperature?** *

Mark only one oval.

○ Never
○ Rarely
○ Sometimes
○ Often
○ Always

12. **How often did you found the room empty and the Air Conditioning system turned on?** *

Mark only one oval.

○ Never
○ Occasionally
○ Sometimes
○ Often
○ Always

13. **How often did you found the room with poor air quality due to the windows being closed for too long?** *

Mark only one oval.

○ Never
○ Rarely
○ Sometimes
○ Often
○ Always

14. **How often did the noise level become too high to keep the concentration in your work?** *

Mark only one oval.

○ Never
○ Rarely
○ Sometimes
○ Often
○ Always

Skip to question 17.

APDC Room

These questions are refering to the room and wokplace assigned to you in APDC.

15. **Why do you prefer to work outside the APDC room?** *

____

____

____

____

____

16. **How satisfied are you with the following aspects of your assigned workspace?** *

Mark only one oval per row.

	Very dissatisfied	Dissatisfied	Indifferent	Satisfied	Very satisfied
Noise level	○	○	○	○	○
Ventilation	○	○	○	○	○
Lighting	○	○	○	○	○
Temperature	○	○	○	○	○

Project Planning

These questions are about the planning of your APDC project.

17. **Which were the more significant challenges in planning your project?** *

Tick all that apply.

☐ Poorly defined goals.
☐ Breaking down the project into smaller and achievable goals.
☐ Predicting how much time a task would take to complete.
☐ Assigning similar workload to all group members.
☐ Managing the different schedules of team members to work together or to arrange meetings.
☐ Assigning tasks to group members according to the different skill sets.
☐ Communicating work progress with the team and vice-versa.
☐ Other: ____

18. **How hard did you find to create a work plan for your project?** *

Mark only one oval.

	1	2	3	4	5	
Very Easy	○	○	○	○	○	Very Hard

19. **How hard was it to keep up with your initial work plan?** *

Mark only one oval.

	1	2	3	4	5	
Very Easy	○	○	○	○	○	Very Hard

20. **How far from reality was your initial work plan?** *

Mark only one oval.

○ We had to redo it from scratch one or more times during project development.
○ We had to do some major changes to the plan during project development.
○ We had to do some minor changes to the plan during project development.
○ We did not have to change the plan during project development.
○ Other: _______________

21. **How often did you had to change the work schedule of the group (Gantt chart)?** *

Mark only one oval.

○ Never
○ Daily
○ Weekly
○ Monthly
○ Other: _______________

22. **How hard was it to predict how much time a task would take to finish?** *

Mark only one oval.

	1	2	3	4	5	
Very Easy	○	○	○	○	○	Very Hard

23. **How hard was it to conciliate your work schedule with your colleagues to arrange "full-group" meetings?** *

Mark only one oval.

	1	2	3	4	5	
Very Easy	○	○	○	○	○	Very Hard

24. **How often did you found the room too crowded or too noisy to have a group meeting to discuss essential phases of the project?** *

Mark only one oval.

○ Never
○ Occasionally
○ Sometimes
○ Often
○ Always

25. **How hard was it to conciliate your work schedule with your colleagues to work on tasks together?** *

Mark only one oval.

	1	2	3	4	5	
Very Easy	○	○	○	○	○	Very Hard

26. **How often did you "got stuck" waiting for a colleague to finish his task?** *

In cases where your next task could only be started after he/she was finished.
Mark only one oval.

○ Never
○ Occasionally
○ Sometimes
○ Often
○ Always

27. **Do you consider that your ability to make better work plans increased during the semester?** *

Was there an increase of precision in predictions made later in the development process than before the development started?
Mark only one oval.

○ Yes
○ Maybe
○ No

Cyber-Physical Systems

Cyber-Physical Systems are physical systems enriched with cyber components. A Smart System can be applied to houses, offices, rooms, etc., and the main goal is to improve the users' experiences. As an example, think of a Smart House, with sensors and actuators that regulate the house temperature automatically.

28. **Do you think that an automatic system that controls the room temperature according to users' preferences and outside temperature would be beneficial for the work environment and improve work efficiency?** *

Mark only one oval.

○ Yes
○ Maybe
○ No

29. **Do you think that an automatic system that controls the intensity of the artificial lights, also turning them on and off when required, would be beneficial for the work environment and improve work efficiency?** *

Mark only one oval.

○ Yes
○ Maybe
○ No

30. **Do you think that a system where the noise level of each worker/group is measured and people get notified that they are being too noisy would be beneficial for the work environment and improve work efficiency?** *

Mark only one oval.

○ Yes
○ Maybe
○ No

31. **Do you think that a system where people get notified to open the room windows to provide some air renewal, would be beneficial for the work environment and improve work efficiency?**

Mark only one oval.

○ Yes
○ Maybe
○ No

32. **Do you think that a tool that helps the project planning and management by making more realistic predictions would be beneficial for the work environment and improve work efficiency?** *

Mark only one oval.

○ Yes
○ Maybe
○ No

33. **Do you think that a tool that helps your team to manage the schedules of all the members more efficiently would be beneficial for the work environment and improve work efficiency?** *

Mark only one oval.

○ Yes
○ Maybe
○ No

34. **How would you classify the importance of implementing the following Cyber-Physical features for improving the planning and development of projects in APDC's rooms?** *

Mark only one oval per row.

	Very important	Important	Somewhat Important	Indiferent
Automatic Lighting	○	○	○	○
Noise Control Mechanism	○	○	○	○
Automatic Ventilation	○	○	○	○
Automatic Temperature	○	○	○	○
Project Planning	○	○	○	○
Schedule Management	○	○	○	○

35. **Would you prefer a totally automated Smart Room system, or one that requires some human interaction to function, but in return gives a more personalised experience?** *

For when, for example, the system calculates that the temperature of the room should be 25ºC, but all the occupants inside prefer it to be 22ºC in that particular situation.
Mark only one oval.

○ Totally automated
○ Partially automated, requiring human interaction for some features.
○ Not automated at all.

36. **In the context of a Cyber-Physical System, can you think of any smart mechanism that would improve the work environment not mentioned above?**

Imagine that any type of information is gatherable and that any physical component can be interacted with. The goal of this question is not for you to provide an in-depth explanation of how it would work, but only the general idea of it, for example "A system that checks how much is missing for completing a task, and performs or suggests changes to the Gantt chart", although you can elaborate on it if you want.

APPENDIX B

QUESTIONNAIRE 2

Perceived Productivity Questionnaire

This small Questionnaire aims to assess the percentage of work you have completed this week when compared to the expected. It is part of the research work under the context of the dissertation of Tiago Caldinhas.

*Required

1. In what room is your project group working? *

   Mark only one oval.

   ○ Lab 116
   ○ Room 240

2. How would you evaluate your amount of completed work, when compared to your expectations at the beginning of the week? *

   Mark only one oval.

   ○ 0-50% : "This week was realy bad productivity-wise. I did less than half the work I expected."
   ○ 50-100% :"This week was bad productivity-wise. I did more than half, but still less work than I expected."
   ○ 100%: "This week was satisfactory productivity-wise. I did all the work I expected."
   ○ 100-150%: "This week was good productivity-wise. I did more than the work I expected."
   ○ 150-200% : "This week was really good productivity-wise. I did almost double the work I expected."

APPENDIX C

QUESTIONNAIRE 3

Workspace Satisfaction

This small questionnaire aims to assess the overall satisfaction of the APDC students with their work environment. It is part of the research work under the context of the dissertation of Tiago Caldinhas.

*Required

1. In what room is your project group working? *

Mark only one oval.

○ Lab 116

○ Room 240

2. How would you classify your work environment, in terms of the quality of working conditions? *

Mark only one oval.

	1	2	3	4	5	
Very bad work conditions	○	○	○	○	○	Very good work conditions

3. How satisfied are you with your work environment, regarding the noise levels experienced? *

Mark only one oval.

	1	2	3	4	5	
Very dissatisfied	○	○	○	○	○	Very satisfied
