Institute of Architecture of Application Systems

University of Stuttgart
Universitätsstraße 38
D–70569 Stuttgart

Bachelorarbeit

Impact on Smart Technology on Energy Use in University Offices: A Case Study

Lukas Müller

Course of Study: Software Engineering

Examiner: Prof. Dr. Marco Aiello

Supervisor: Dr. Ilche Georgievski

Commenced: November 1, 2023

Completed: May 2, 2024

Abstract

In order to oppose various causes of the climate crisis, many measurements are developed and evaluated worldwide. One important step towards carbon neutrality and therefore to stop global warming, lies in reducing energy consumption of every type. One of the biggest opportunities to save energy in different forms, lies in the building sector. Especially office rooms often demand more energy than necessary due to inefficient handling of different resources. Hence, this work proposes a simple, low cost and smart system to automatically control a thermostat, workstation and lamps in an office environment in order to save as much energy as possible. Applying the proposed system leads to electric energy savings figuring at least 8.6 kg a year per office only on controlling power supply of one workstation. Furthermore, promising results about possible savings in electricity are examined by automatically controlling lights. Heating energy utilization can be additionally reduced with the use of smart thermostats, especially on weekends and outside working hours, by turning off thermostats. It is shown, that using only low cost equipment in form of sensors and actuators can reduce office energy demands and therefore gives perspectives to reduce global warming.

Kurzfassung

Um verschiedenen Ursachen der Klimakrise zu entgegnen, werden weltweit Maßnahmen entwickelt und evaluiert. Ein wichtiger Schritt in Richtung CO_2-Neutralität and damit zum Stopp der globalen Erwärmung liegt im Reduzieren jeglicher Art von Energieverbrauch. Eine der größten Möglichkeiten, um Energie in verschiedenen Formen zu sparen, liegt im Gebäudesektor. Vor allem Büroräume verbrauchen häufig mehr Energie als notwendig aufgrund eines ineffizienten Umgangs mit verschiedenen Ressourcen. Daher wird in dieser Arbeit ein einfaches, kostengünstiges und intelligentes System vorgeschlagen, welches ein Thermostat, einen Arbeitsplatz und Lampen in einer Büroumgebung automatisch steuert, um Energie bestmöglich zu sparen. Die Anwendung des vorgeschlagenen Systems führt zu elektrischen Energieeinsparungen von mindestens 8.6 kg pro Jahr und Büro, nur durch das Steuern der Stromversorgung eines Arbeitsplatzes. Darüber hinaus werden vielversprechende Ergebnisse über mögliche Stromeinsparungen durch die automatische Steuerung der Beleuchtung erzielt. Der Heizenergieverbrauch kann insbesondere an Wochenenden und außerhalb der Arbeitszeiten zusätzlich durch den Einsatz von intelligenten Thermostaten reduziert werden, indem diese entsprechend ausgeschaltet werden. Es wird gezeigt, dass der Einsatz von kostengünstigen Geräten in Form von Sensoren und Aktoren den Energiebedarf im Büro reduzieren kann und somit Perspektiven bietet, die globale Erwärmung zu verringern.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

One of the biggest crises humanity faces currently and which effects can already be experienced today, is the climate crisis. All the greenhouse gases lead worldwide to hotter temperatures, more severe storms, increased droughts and therefore also a lack of food in effected regions [Nat24].

The biggest causes for climate change are deforestation, fertilizers containing nitrogen and of course all kinds of burning fossil energy sources like coal, oil and gas [EU24]. Especially our traffic infrastructure in the form of planes, ships, cars and trucks leads to many burnt fossil energy sources, and with that to tons of CO_2 emissions and other greenhouse gases. But the biggest amount of fossil energies are burnt in the electricity and heat production sector, e.g. in oil or gas-fired power plants [RRR20].

Though we increasingly try to avoid producing greenhouse gases with modern technologies like electric cars and for the energy sector with renewable energy systems like hydroelectric power plants or photovoltaic systems, we still produce too much greenhouse gases, so we cannot stop the global warming sufficiently. Making it even worse, the global CO_2 emissions are higher than ever before. Current policies will likely reduce greenhouse gas emissions in the future, but the global warming forecasts still predict the average temperature to increase between 2.5 °C and 2.9 °C by 2100 compared to pre-industrial times, considering availability of historical readings. Even a scenario, where each country reduces its respective emissions according to their reduction pledges would probably lead to a warming of 2.1 °C for the same period of time [RRR23].

In addition to trying to produce energy in a more climate friendly way, it is also possible to improve our carbon footprint by decreasing the energy consumption of existing systems. Regarding this, one option to reduce the required amount of energy is to install smart systems, that turn off devices that are not needed at the moment and re-power them on demand. The advantage of this approach is, that it can be used in nearly every environment. Thus, parts of big data centers can be turned off, when the demand is low, cars can turn off their combustion engine when waiting for a traffic light to become green and buildings like offices or homes can use smart technologies to control the power of lights, thermostats, work stations and more to save energy.

Diving deeper into the energy efficiency of buildings, this might be one of the most relevant sectors to reduce energy demands and therefore greenhouse gas emissions, since buildings are one of the largest producers of those. The German Federal Ministry for Economic Affairs and Energy claims that buildings are responsible for 35% of the total annual energy consumption. Converting this number to the thereby produced greenhouse gas emissions, buildings take responsibility for one third of the total annual greenhouse gas emissions like CO_2 [EB15]. A global increase of energy demand in buildings by annually 1% over the past decade is another figure describing the high impact buildings have in global warming [IEA23]. Enormous improvements in building's energy efficiency will be required to achieve climate neutrality of Germany and the European Union (EU) by 2050 [EU19].

1.2 Problem Statement

The University of Stuttgart, as well as many other institutions, companies and societies, explores ways to reduce its energy consumption. Along with already carried out measures like the installation of new ventilation systems, refrigerators, replacing old lights with LEDs and even doing energy-saving weeks in winter, the University continuously tries to find additional ways to save energy in its respective buildings and with that reach its aim of reducing the energy consumption by 20% by 2024 [Stu]. This especially arises the need to gather real-time data of the university's facilities and intelligently manage its resources with the gathered data. Since many facilities of the university are offices, where it is known, that the energy is not efficiently used due to occupant behavior [SH17], it becomes increasingly important to try reducing office's energy demands. On top of today's technological possibilities to automate monitoring and controlling of different devices and equipment, the question arises, how the University of Stuttgart can use Internet of Things (IoT) devices and technologies to manage its offices in the most efficient way.

Following these considerations, the objective of this bachelor thesis is to conduct a pilot project with an implementation and evaluation of a smart office system in a university office setting to monitor environmental conditions in real-time and optimize the energy use according to the respective conditions. Therefore, the thesis aims on creating a smart office, that not only reduces energy consumption and costs, but also improves comfort and productivity of its occupants.

Another worth mentioning fact is, that the pilot project takes place in an interdisciplinary setting and thus involves a variety of parties. To achieve accurate and promising results, these parties need to be coordinated and managed to achieve the objective. Involved parties are the Green Office of the University of Stuttgart and its occupants, the department Service Computing from the Institute of Architecture of Application Systems (IAAS), and the "Technische Leitwarte Stadtmitte". The Green Office, which is part of the university's rector's office, therefore provides the installation premise, the IAAS offers hardware, knowledge and the implementation, whereas the "Technische Leitwarte Stadtmitte" is responsible for organizing electrical work.

Aiming on decreasing the energy consumption as much as possible, while having low costs for the equipment and implementation of the proposed system, the research question is derived as follows:

RQ What are the achievable energy savings of one office room with the use of cheap sensors and actuators compared with manual control of environmentally friendly occupants?

Dividing this research question into more granular sub-questions enables the possibility to answer it in a more understandable and precise way. So the following sub-questions are defined:

SQ1 What are the possibilities for data acquisition through the use of cheap sensors?

SQ2 How would the architecture of such a simple and low-cost system look like?

SQ3 What are the possibilities to compare and analyze the gathered data to determine what energy savings would be possible through the proposed system?

1.3 Proposed approach

To answer the research question and address the problem of saving energy in the university's office buildings, a simple application was developed to create a smart environment in the Green Office's manager's room. The application only uses simple sensors to track the basic conditions of the office, like the presence of a person, the light level and the temperature. Due to the sensors' values, the systems switches light and desk power on or off. Furthermore a smart thermostat, meaning the thermostat can be turned on and off remotely, controls the radiator valve depending on the room temperature and the presence of an occupant.

With the implementation and installation of the system aiming on saving energy in an easy and efficient way, it is sufficient to evaluate the system's effectiveness especially in regard to possible energy savings. To analyze the energy effectiveness of the system, an experiment was conducted in two steps. The first step of this experiment retrieves baseline data as a comparison base for during the second phase acquired data with the smart system. Finally, especially with regard to the question of how much energy can potentially be saved with the proposed system, the data of both phases are analyzed and compared to detect the achieved energy savings.

1.4 Structure

The work continues with Chapter 2, which contains related work on this topic to get an overview about previous studies, proposed systems and the achieved energy savings regarding different approaches. Afterwards Chapter 3 explains the chosen approach to address the problem statement and therefore the objective of the thesis, before Chapter 4 presents the system implementation and deployment. Furthermore, it is shown, which devices and technologies are used and how the system operates. Chapter 5 continues afterwards with the experimental setup and results gathered from the experiment phases. In Chapter 6, the previously presented results are discussed. This chapter also provides insights on the learned lessons from the problems, that occurred during the study. The work is finalized with a conclusion in Chapter 7, which also provides a small outlook on the future work building up on this thesis.

2 Related Work

One fundamental base of this work is given through the “Planning meets activity recognition: Service coordination for intelligent buildings” article by Georgievski et al. [GNN+17], where the authors installed two smart systems in different environments. The first one controlled devices in two office rooms and a social corner in an office building at the University of Groningen in the Netherlands, while the second system coordinated ceiling lamps of a restaurant, also in Groningen, depending on the natural light level in different areas of the restaurant. Both of the installed systems were afterwards evaluated with regard to energy savings, usability, accuracy and performance under increasing complexity. Especially with the aim of saving energy in the considered buildings, their proposed office system definitely shows, that smart controlled environments can be really useful in handling energy resources efficiently and thus can reduce energy demands significantly. For example considering the energy savings only in the office/social corner installation, Georgievski et al. determined potential energy savings of 75.05%. When separating the electricity consumption reduced from the lamps and workstations, 98.5% of electric energy could be saved with controlling the lamps and 46.9% respectively with managing the workstations. Comparing the electric energy consumption with manual control and the proposed system in the restaurant setting resulted in electricity savings of 89%. This work is similar to the one in this bachelor thesis regarding problem statement, installation environment and proposed system, thus making it this work’s base.

Results regarding financial benefits of smart office systems were achieved by Salosin, Gamayunova and Mottaeva [SGM20]. They claim, that investing an additional 50% of the costs of a new building into its automation will result in a financial payback within the first two to four years. Moreover Salosin, Gamayunova and Mottaeva determined the operating costs for an automated building in a time span of 20-30 years are 2.5 times below operating costs of a non-automated building. Accordingly, the total costs of owning an automated building will be 1.5 times lower than a non-automated one. The proposed work differs from this thesis especially in terms of experiment time, environment size and main goal, since it compares costs of a whole building in a time span of over two decades to achieve financial benefits.

Other research works tried to separate the different energy savings to another variety of systems. As an example Ahmadi-Karvigh, Becerik-Gerber and Soibelman [ABS19] tested four levels of automation, ordered from a low to a high level, and evaluated the respective data. Experiments also referred to an office environment, since the controlled devices are a computer, a monitor and a lamp. To evaluate the described levels of automation, Ahmadi-Karvigh, Becerik-Gerber and Soibelman used a data set build combined of real data from the experiments described in their previous, similar study ([AGBS18]) and synthetic data. Firstly, energy was saved with each of the proposed levels of automation across all occupants. Secondly, level two and three perform very similar regarding their energy consumption and therefore the potential electricity savings across all occupants. Lastly, level four automation yields the highest energy savings, since it can save up double the amount of electric energy depending on the occupant and compared to level two and three. A good example is therefore one office occupant, where level four automation saves ca.

2.000 Watt-hours a day compared to the respective energy consumption with level two and three automation. Even though Ahmadi-Karvigh, Becerik-Gerber and Soibelman's work shares the same experiment environment, evaluating on four levels of automation makes this approach different, since this thesis only evaluates differences on automatic and manual control.

Harle and Hopper [HH08] examined more interesting results of saving energy in office buildings by controlling the lights according to the presence of occupants. Assuming three different lighting schemes, filtered location logs gave the authors some insights on the electric energy consumption and the possible power savings linked to the comparison of the different energy consumption related to the mentioned lighting schemes. Therefore, Harle and Hopper defined their respective lighting schemes as follows:

1. All lights are turned on 24 hours a day
2. The first office owner entering turns on the lights in the morning and the last leaving owner turns the lights off.
3. The lights are switched off automatically when the room is vacant.

Especially comparing data on the second and third lighting scheme in these types of rooms leads to interesting results. Firstly, in all room types light- and room-hours can be saved by automatically switching lights on and off compared to both other lighting schemes. Secondly, the authors examined, that the possible energy savings on these lighting levels were the highest in corridors, followed by the communal rooms and lastly by the offices. Since Harle and Hopper compare electricity savings with controlling only lights triggered by movement, but additionally comparing different schemes, their work differs from this thesis in these objectives.

Instead of controlling devices in office environments, Chiaraviglio and Mellia [CM10] propose a solution called PoliSave to provide a power management tool for Campus PCs. The application is built upon a web-based client-server architecture allowing users to schedule their PC's power states. Technologies like Wake-On-Lan are used to control the respective PCs. The main aim is to avoid users frustration arising from possibly long power-downs and bootstrap times of PCs to therefore motivate users to save energy since the aforementioned disadvantages are reduced with PoliSave. Analyzing the proposed system's possibilities to reduce energy consumption seems to be rather promising. According to Chiaraviglio and Mellia, PoliSave reduces the average PC uptime from ca. 16 hours to 9.7 hours during working days. These ca. six hours of uptime reduction for each PC on average leads to electric energy savings of about 0.6 kW/h per PC and per day. Based on this data, determining possible economical benefits for the University of Torino results in a quarter million Euros per year. PoliSave is an interesting approach aiming on reducing energy consumption in universities, which is similar to this thesis' approach, although PoliSave tries to decrease energy demands for students and not for the university's staff and their respective offices.

Aiming especially on energy savings in university buildings, Pujani, Akbar and Nazir [PAN19] analyze data about power and energy consumption on three buildings of Andalas University in Indonesia. Therefore, a real-time energy monitoring system stores data in five minute intervals for each building. Energy patterns about daily consumption and weekly load power are plotted for three months data in order to catch opportunities on energy savings in the respective buildings by reviewing and analyzing relationships in both patterns. Significant savings could be performed especially outside working hours according to Pujani, Akbar and Nazir. Therefore, energy savings of 21.06%, 20.17% and 9.85% for the engineering faculty, lecturing and central library are examined by the authors. Comparing the proposed work to this thesis' objective, they try to save energy in similar institutions. Beyond that, Pujani, Akbar and Nazir focus on a larger environment than the thesis objective, since they save energy in three buildings, while this thesis aims on achieving energy savings in an one office environment. Additionally, the objective of this thesis is based on shorter time intervals, since it tries to reduce the energy consumption immediately based on different sensor readings, while Pujani et al. focus their work on providing a more general approach.

3 Approach

The following chapter describes the chosen approach to address the problem statement and answer the research questions. It presents the methodology of this work, a description of the installation premise and the system's requirements, which is followed by the explanation of the system design.

3.1 Methodology

Fig. 3.1 visualizes the methodology and its respective parts as a data flow diagram. The methodology starts with an office inspection at the installation premise, before continuing with understanding the office occupant's working style. While the first of these steps aims on creating a first installation draft, the latter one improves this draft. A following requirements analysis finalizes the installation plan. Afterwards baseline consumption data is gathered with a simple script and sensors. In parallel, the installation plan is implemented and the system deployed after the baseline data acquisition. Another experiment phase achieves the objective to gain information about the system's energy consumption. Both phase's data points are finally analyzed and compared. Each step is described in detail in the following.

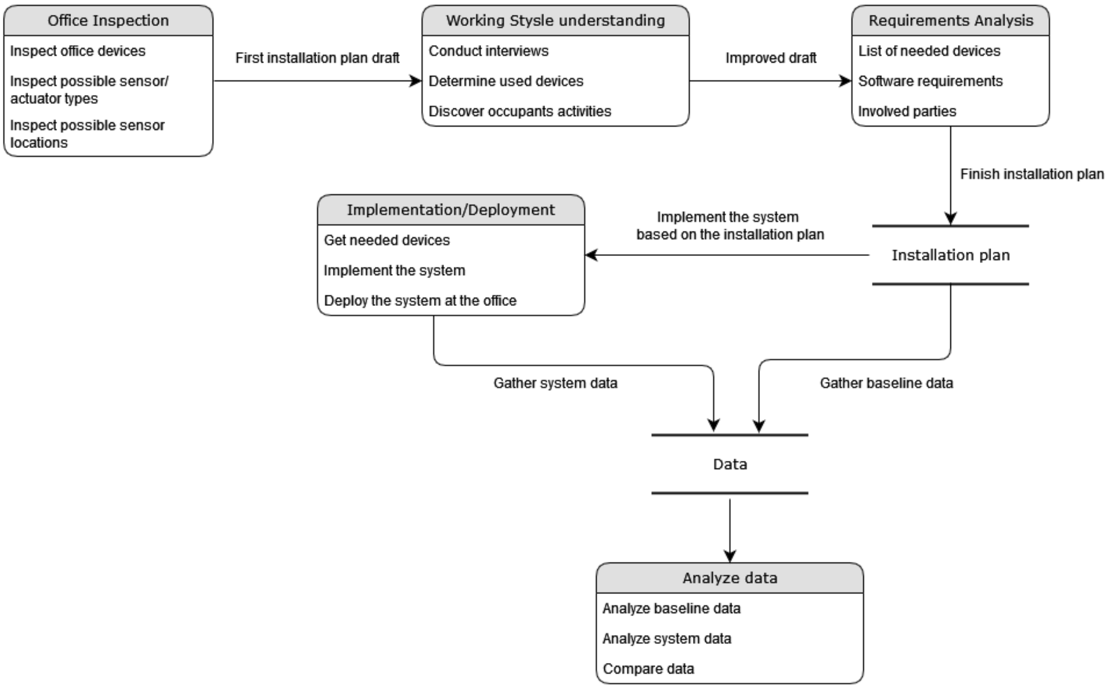


Figure 3.1: Methodology as a data flow diagram

3.1.1 Office Inspection

The first step to address the proposed problem statement is an office inspection. This is carried out under the assumption of preceding literature work to gather office automation possibilities in form of sensors, actuators and technologies. With the obtained information from the literature research and the office inspection, it becomes possible to create a first plan of which devices could be controlled automatically in the premise. Furthermore, the plan could be enhanced by possible locations for sensors and actuators.

3.1.2 Occupant Working Style Understanding

Subsequent to the office inspection, interviews are conducted to retrieve information on the occupants working style and behavior. Under the presumption of ideas about possible devices and their installation locations from the previous step, these interviews are supposed to gather information on performed activities in the premise and therefore to decide which devices would be useful to automatize the given environment. Accordingly, this step could perhaps alter the before conducted plan, since not every device is used regularly and thus must not be addressed by the system. Therefore, enhancements regarding expenses for installing the proposed system could possibly be made to decrease installation costs and thus increase possible financial benefits.

3.1.3 Requirements Analysis

Out of the preceding steps and the gathered information, a requirement analysis is performed in order to set up the final installation plan including software and hardware, functional and non-functional requirements. Therefore, this step outputs a list of needed devices, software features and involved parties to install a smart system in the office environment. Furthermore, defining possible ways of data collection and analysis becomes necessary in order to evaluate the gathered data and results. Conducting the requirements analysis ultimately defines the system design, implementation and deployment.

3.1.4 Implementation and Deployment of the System

According to the requirements analysis and the previous preparation steps a smart system is developed, installed and deployed in the premise according to the elaborated installation plan. Therefore, the proposed solution tries to satisfy the determined requirements with the ultimate goal of saving energy in the best possible way according to the proposed problem statement.

3.1.5 Gather and analyze data

To finally evaluate the proposed solution's performance, two test phases are conducted. In the first phase, baseline data is gathered to build a basis for comparison. Specifically, there is no automatic control of any device during this first phase. Instead it is only tracked, how high the energy consumption of the respective devices is, when only controlled manually through the occupant. This first phase is conducted in parallel to the previous implementation and deployment step. Afterwards, during the second phase, data is gathered again, but now with the system deployed and running. The data recorded in this stage gets compared with the previously ascertained baseline.

3.2 The Office

The case study takes place in the rector's office of the University of Stuttgart. Precisely, the proposed system is installed in the office of the university's Green Office manager. The room features four ceiling lamps, one desk, an extra table, one radiator and a window. In the room, the desk is placed in front of the window, the small extra table is located at the room's opposite site. One light switch controls the two ceiling lamps closest to the window, while the other two lamps are each controlled solely by separate switches. A chair is placed in front of the window and desk. The desk, in turn, builds the occupant's workstation including a power strip providing electric energy to two monitors, a docking station and one desk lamp. A manual power control device is plugged before the desk power strip. The radiator is placed under the window and therefore also next to the workstation. Fig. 3.2 shows a layout of the office.

3.3 Requirements

The most important requirement the system needs to fulfill, is to handle the energy resources in the most efficient way. This requirement arises directly from the problem statement. Additionally, it is important to avoid any restrictions for the office's occupants. Referring to this, the system should not control devices in an undesirable way, meaning it sends commands to devices, that disturb the occupants at their work. An example would be, that the system automatically sends a command to turn of the monitors on a desk, while the occupant is working with the monitors. Another determined requirement would be, that data is persisted with regard to easy access and good performance. Referring to this, it is especially important to store the data points in a way, it can be analyzed between baseline and the deployed system. Additionally it is necessary to store possible personal information according to data security guidelines. To ensure avoiding restrictions for the user and generate accurate and continuous data, it is further important to build the system in a sufficiently robust way, which would especially mean, that the system runs for at least one test phase period without interruptions. Another requirement is given through external factors, that might influence the results elaborated in this thesis. Therefore, weather data needs to be stored in order to compare baseline information more accurate to the data gathered with the proposed system. Besides, an extending requirement can be the availability of an interface, through which the occupant can edit thresholds without the need of understanding the application. Furthermore, an interface could also provide some insights on current sensor readings.

The highest prioritized requirements are efficient handling of energy resources, avoiding restrictions for occupants and the system's robustness.

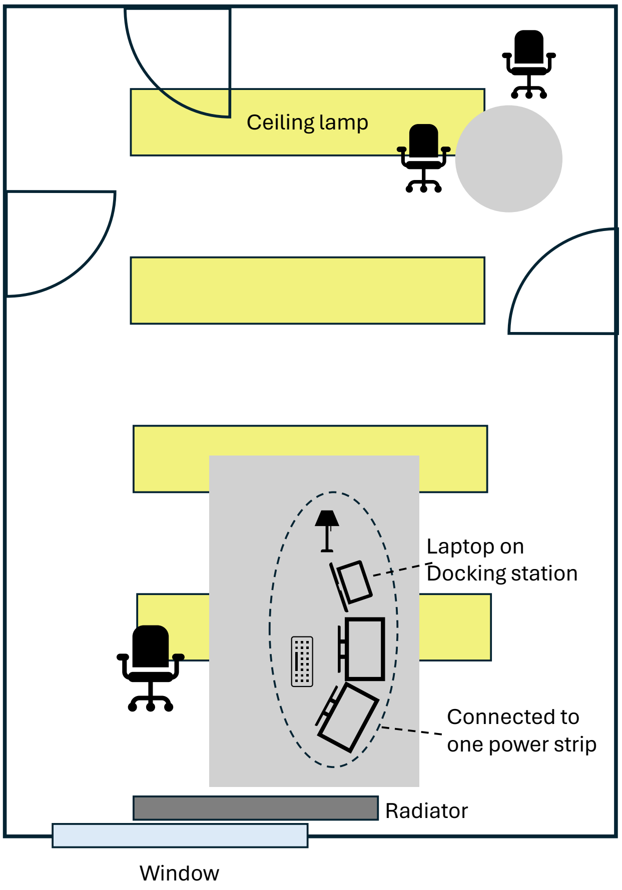


Figure 3.2: Schematic representation of the office. The quarter circles on the left, right and top wall represent doors, the yellow rectangles ceiling lamps and the two light grey areas the desk and table. Depicted devices on the desk are from top to bottom a desk lamp, a laptop on a docking station and two monitors, left to these is a keyboard. On the left side of to the desk, as well as next to the table are chairs.

3.4 System Design

Five components build the proposed system of this work. Firstly, there are sensors providing respective value readings. These values are used on the one hand to control different devices based on the corresponding environmental conditions, which itself are described by the value readings, and on the other hand provide data points to the server to store them. A database stores all the data generated from sensor readings and therefore is the second component. Access to the database is handled via the internet, since an online database is used. Thirdly, the already mentioned server acts as a connection between all components and controls the devices, retrieves weather information through the internet and stores data points to the database. Moreover, there are also actuators, that get control commands from the server and execute them. All actuator devices are also sensors in this work. Lastly, a simple command line interface allows the user or occupant to change some

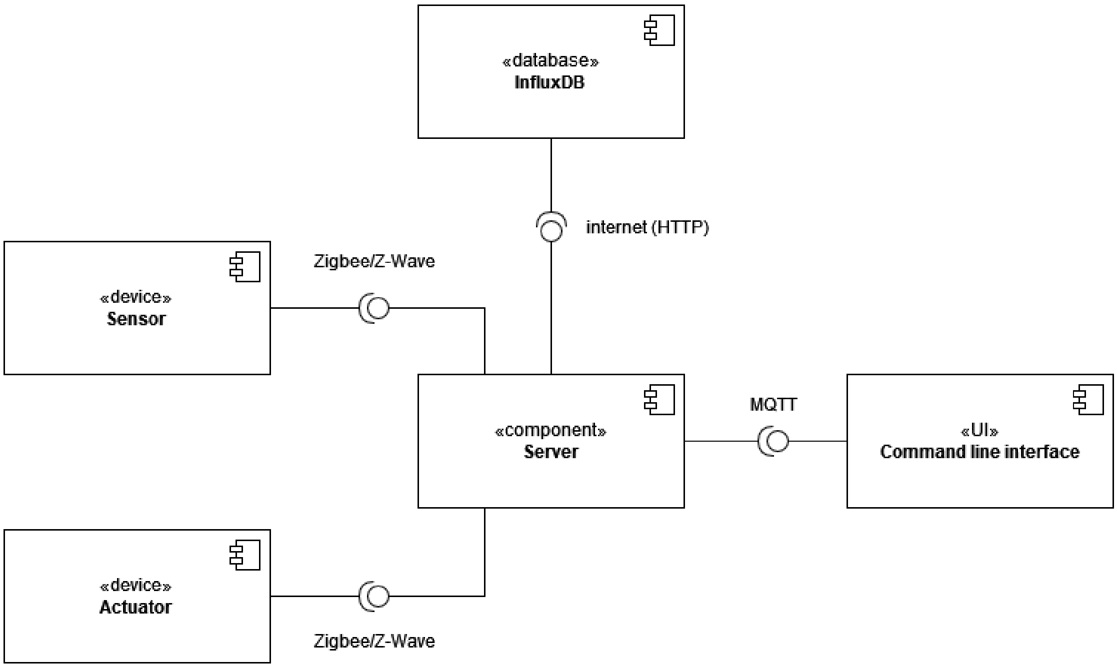


Figure 3.3: Component diagram depicting the proposed system.

thresholds according to personal preferences. The command line interface sends new thresholds to the server via the Message Queuing Telemetry Transport (MQTT) protocol. Z-Wave and Zigbee form networks of IoT devices to communicate between server, sensors and actuators. Figure 3.3 shows a diagram of the system and its respective components.

4 System Implementation and Deployment

4.1 Background Thoughts on Implementation and Deployment

Based on the installation premise's sighting, analyzed interviews with the occupant and aiming on fulfilling the requirements, an installation plan is created. Handling energy resources in the most efficient way while still having low device costs and easy implementation of the respective application additionally influenced the installation plan. Derived from the interviews, the only scenarios happening in the office are discussions, attending online meetings and doing normal work. Accordingly, a discussion is defined as two or more people talking to each other in person, while attending online meetings involves only the office's occupant being in an online meeting. Furthermore, normal work is defined as single work without any conversation at all, which would mean more precisely, the office's worker answers mails, researches something on the internet or does some other work on the PC.

Analyzing the three scenarios with regard on the needed sensors and actuators results in only needing to separate the states "presence" and "absence". This follows from the determined scenarios, since all of them might need the lights, heat and the desk with PC. While for the scenario of normal work and attending an online meeting, this is rather obvious, since the occupant does neither want to freeze, nor to work in a dark room or without their PC, for having a discussion, this is a bit more complex. When discussing, there might be the need for a warm environment and enough brightness to show something to the discussion partner, but the PC won't be needed in many cases. So, due to the demand of showing something to the discussion partner on the PC or making a little research according to the discussion topic, the PC could as well be needed. Further, discussions are the most unlikely scenario happening. So, all the possible scenarios need or at least might need the same devices and artifacts, which lead to only separating between the two states absence and presence of the occupant, which is also grounded in trying to hold the system's expenses as low as possible by reducing demanded sensors.

To fulfill the needs of tracking absence and presence of the office's occupant, the installation needs to control only the two lamps, that are used by the employee working in the office, the desk power strip and the radiator valve. Aiming on low device and installation costs, cheap devices are used, that work with the same or at least similar technologies regarding their operating principle. This results in using the same actuator-sensor device for the electric controlled devices, namely the desk power strip and the ceiling lamps. An additional multi-sensor includes a passive infrared sensor (PIR) to measure movements, a thermometer measuring the temperature, and a light sensor reading the illuminance values. Furthermore, a smart thermostat is used to control the radiator. Even though the multi-sensor uses the same communication technology as the installed thermostat, the electric actuator-sensor devices rely on another technology. Both technologies though work via a network connected to the server with an USB-Stick.

The following sections name and explain the used technologies, as well as the corresponding devices based on these technologies.

4.2 Technologies

The MQTT protocol, Z-Wave and Zigbee build the proposed system's base technologies. While MQTT is used for inter-script communication between the different Python scripts, both, Z-Wave and Zigbee, build networks used to control devices and getting sensor readings. So every installed actuator and sensor is part of either a Zigbee or a Z-Wave network to communicate with a respective controller or gateway.

MQTT (`https://mqtt.org/`) is a standard messaging protocol created by OASIS (`https://groups.oasis-open.org/home`). It was developed for the IoT and is designed as a lightweight publish/subscribe messaging protocol. This benefits in connecting remote devices with small code footprint and low network bandwidth. Therefore, MQTT nowadays finds use in many different industries. The protocol's main components are a broker and multiple clients. While the broker handles all incoming messages sent from connected publisher clients by forwarding them to corresponding subscriber clients, a client can be both, subscriber and publisher. Clients publish their messages with a specific topic and the broker sends the message to all clients, that have subscribed to the correct topic. Furthermore, MQTT uses different Quality of Service levels to define the reliability of the message delivery. Accordingly, messages can be sent with the following levels of reliability: at most once, at least once or exactly once. [MQT]

For the proposed system, the open source Eclipse Mosquitto MQTT broker (`https://mosquitto.org/`) was used and the clients were implemented with the Python Paho-MQTT-Library (`https://pypi.org/project/paho-mqtt/`). MQTT handles the inter-script communication between the Zigbee, Z-Wave and command line interface Python scripts.

The next used network technology is Zigbee developed by the Connectivity Standard Alliance (`https://csa-iot.org/`). It builds a reliable, lightweight and low-power mesh network to communicate with different devices [All]. Coordinators, routers and end devices are the three types of nodes a Zigbee mesh network contains. While there is only one coordinator per network to store network related data, like security keys, there can be more routers and end devices. Therefore, routers relay messages as intermediate nodes, while end devices are only capable of communicating with the coordinator or a router, but without being able to relay messages [Ros17].

The proposed system uses a Zigbee mesh network to get the energy consumption of the electric devices in the office, as well as turning them on and off. A USB-Stick works as a communicator to the network coordinator and is plugged into the server to connect the network devices to it. To work with the actuator-sensor devices via the Zigbee network, the python-plugwise library was used (`https://github.com/aequitas/python-plugwise`).

Finally, Z-Wave is the last mentioned network technology used in the proposed system. Similar to Zigbee and MQTT, Z-Wave is a wireless communication protocol. The technology also uses mesh networking and as well as Zigbee allows three types of nodes: a controller, routing nodes and end nodes. Controllers are the administrators of a Z-Wave network, setting up the network and keeping track of all connected devices. Other than in Zigbee networks, there can be multiple controllers in a Z-Wave network. Routing nodes know all their neighbors and repeat signals in order to extend the network's range to more distant nodes. They are also capable of sending unsolicited messages to every node they can route to. End nodes also know all their neighboring nodes, but can only communicate with nodes, from where they receive messages [V24].

This bachelor thesis' system takes advantage of the Z-Wave technology by collecting data from a multi-sensor over the Z-Wave network. Furthermore, the smart thermostat is also controlled and accessed via Z-Wave. The used Z-Wave network controller is an USB-Stick, that is also plugged into the server. A Python script for accessing the stick and therefore the Z-Wave network devices is built with the python-openzwave library (`https://github.com/OpenZWave/python-openzwave`).

4.3 Sensors and Actuators/Devices

As the base device, a Raspberry Pi 3 Model B+ (`https://www.raspberrypi.com/products/raspberry-pi-3-model-b-plus/`) is used as a server to gather sensor data from the linked sensors and to control all the connected devices based on the current sensor readings. Additionally, the Pi stores respective data points created from sensor readings to an InfluxDB (`https://www.influxdata.com/`) cloud database, i.e. an online time series database, to enable remote access. Essentially, the server runs two Python scripts, where one represents the code related to the Zigbee devices and the other one links the Z-Wave equipment, respectively. Another Script only implements a command line interface to query the application for current sensor readings and providing commands to change the lower and upper bound illuminance thresholds, as well as the temperature threshold. Separating the application by their used technologies is reasoned in both of them must open a certain USB port to control the respective devices via the connected USB-Stick, that are the Z-Wave's and Zigbee's network administrators. To control the Z-Wave devices, the Aeotec Stick Gen 5 (`https://aeotec.com/products/aeotec-z-stick-gen5/`) is used, while the Zigbee network is accessed with the Plugwise (`https://www.plugwise.com/?lang=en`) USB-Stick.

The Zigbee network furthermore includes one Plugwise Circle+ and further two Circle nodes. Both, Plugwise's Circle+ and Circle nodes are little plugs for power sockets, providing an energy meter and the capability to turn on and off the electric power output. While Circle+ plugs are used as administrative coordinator nodes of Zigbee mesh networks, the two Circle nodes and the USB-Stick build routers of a Zigbee network. In the proposed system, the Plugwise Circle+ plug controls is plugged before the desk power, while the Circle nodes control the two ceiling lamps.

Lastly, the Z-Wave network consists of the mentioned USB-Stick as the network's controller, a multi-sensor to determine the current temperature, movements and illuminance. Additionally, a smart thermostat controls the radiator valve. As multi-sensor, Aeotects MultiSensor 6 (`https://aeotec.com/products/aeotec-multi-sensor-6/`) is used, the office's radiator is controlled with the Eurotronics Comet Z-Wave thermostat (`https://manual.zwave.eu/backend/make.php?lang=DE&sku=EURECOMET&cert=`). The multi-sensor sends its measured values every 10 seconds to the Z-Wave USB-stick, while the thermostat is set to a set-point temperature of 20 °C, which can be changed directly at the thermostat. Depending on the measured temperature of the multi-sensor and the presence state of an occupant, the thermostat either is set to Off-mode or Heat-mode. It is not possible to control the thermostat target temperature remotely via the Z-Wave network. Therefore, when changing the set-point temperature on the thermostat, the set target temperature command provided by the command line interface must be executed accordingly for the system to work correctly.

4.4 Deployment Setup

4.4.1 Device Deployment

All the sensors and actuators are installed according to Fig. 4.1. A Plugwise Circle+ node is plugged in the power socket, that provides power to the desk power strip. The desk power strip supplies both monitors, a docking station and a desk lamp with electric energy. Both Circle nodes are connected to the ceiling lamps. Mounted on the wall above the desk and oriented towards the desk chair, is the multi-sensor. Lastly, the smart thermostat is mounted on the radiators valve.

4.4.2 Application Implementation

The general and simplified application flow is described by the flow chart depicted in Fig. 4.2. Summarizing the application results in an endless loop checking the different sensor readings and reacting in real-time to it.

Not depicted in Fig. 4.2 are the data acquisition and commands send by the command line interface. Data points are stored every minute. They include weather data of Stuttgart, electricity consumption data for all three Plugwise plugs, as well as light and temperature related data, containing for example the measured illuminance, temperature and thermostat mode. Change of the upper and lower illuminance thresholds and the temperature threshold is enabled through the command line interface. According to this, it becomes crucial to change the threshold temperature via the provided command accordingly when changing the thermostat set-point, since the system turns off the thermostat as soon as the multi-sensor recognizes a temperature value higher than the threshold. Switching the lights on and off dependent on two different thresholds, the lower and upper illuminance, results from avoiding infinite light switches happening, when only one boundary is used, since switching the lights takes immediate influence on the light level. Therefore, situations might occur, where the lights are turned off according to a high light level, which reversely results in a low light level and thus a turn-on-light signal. Proposing two values, leads to the system turning on the lights for light values below the lower boundary and to turning off the lights for values above the upper threshold. Initially, the lower illuminace boundary is set to 250 Lux, the upper threshold to 400 Lux and the target temperature holds 20°C. The light values being lower than 500 Lux, which is the optimal recommended illuminance for office workstations [len24], is reasoned in the light sensor of the multi-sensor not being on the table and orientated a bit towards the ground. Furthermore, as shown in Figure 4.1, the multi-sensor is next to the window and oriented away from it. These circumstances lead to lower values measured through the multi-sensor. Orientating the device a bit to the floor is reasoned in the sensor targeting the office user to reliably detect the occupant's motions. Additionally, the user interface features an option to print the last measured values.

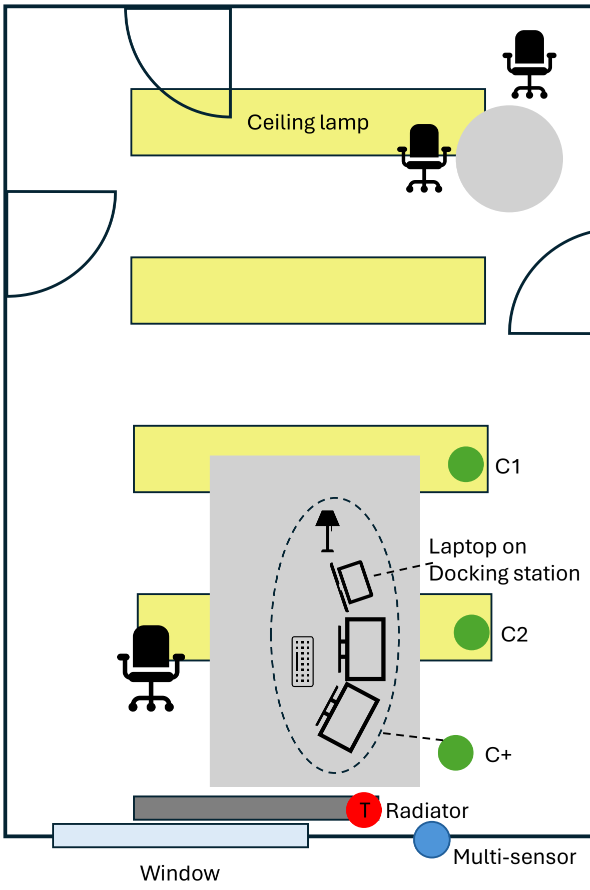


Figure 4.1: The graphic shows a schematic overview of the premise. The quarter circles on the left, right and top wall represent doors, the yellow rectangles ceiling lamps and the two light grey areas the desk and table. Depicted devices on the desk are from top to bottom a desk lamp, a laptop on a docking station and two monitors, left to these is a keyboard. On the left side of to the desk, as well as next to the table are chairs. Green dots symbolize the Plugwise Circle and Circle+ plugs, the red dot shows the position of the smart thermostat and the blue dot displays where the multi-sensor is placed. The two most distant ceiling lamps from the window are normally not used and thus neither controlled or part of the system.

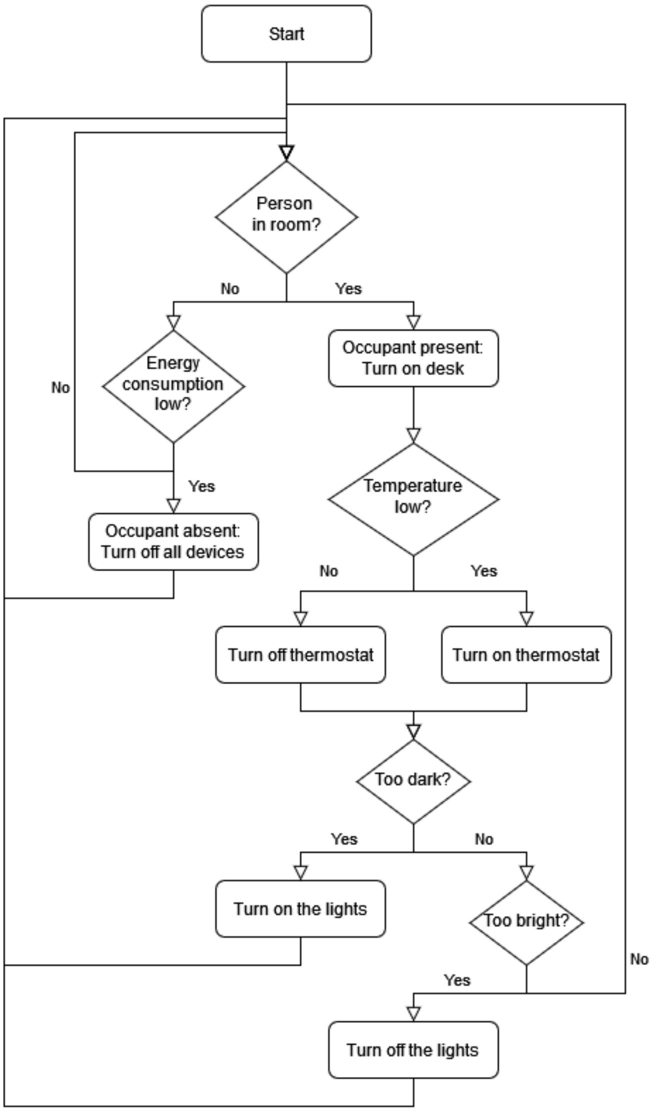


Figure 4.2: Flow chart depicting the proposed application.

5 Experimental Setup and Results

5.1 Experimental Setup and Data Acquisition

To retrieve data needed to evaluate the systems effectiveness in matters of saving energy, two experiments were conducted at the premise. First, the Plugwise plugs were installed according to Fig. 4.1 to retrieve baseline data. Therefore, a simple application only gathered the power consumption of the desk and lamps via the plugs and stored them to the Influx database. Since the proposed system includes also a smart thermostat mounted to the radiator, a way to get baseline data on the radiator was needed to enable comparison between data with and without the smart system. This objective was achieved through a file, that was appended by the office's occupant every time the old radiator thermostat was readjusted. Every entry contains the day, time and new thermostat level. To achieve better and more accurate evaluation options, weather data was acquired additionally. Hence, Hypertext Transfer Protocol requests to the online weather forecast provider OpenWeather (`https://openweathermap.org/`) supplied required data points. The first phase experiments took place in two consecutive weeks, namely between the 11^{th} and 24^{th} March 2024.

After the two weeks of data acquisition to retrieve baseline energy consumption information, the proposed system was deployed. Therefore, the multi-sensor and thermostat were mounted on the wall and radiator, respectively. Additionally, the software to retrieve data and control devices was executed on the server. Furthermore, the radiator baseline file was collected. The second phase then was conducted from 8^{th} to 21^{st} April. Similar to the first phase, weather data and electric energy consumption data acquired from the plugs were stored. According to deploying the additional devices, further data about illuminance and temperature values were retrieved during this phase. These are for example current respective sensor readings, the thermostat mode and currently applied thresholds, since the provided command line interface allowed to edit them from this stage on.

5.2 Retrieved Weather Data

The first retrieved results are the gathered weather data. Especially gained information on measured temperatures can improve results on the thermostat comparison. Fig. 5.1 depicts weather information for the first weeks of both experimental stages, while Fig. 5.2 displays temperature evolution for the second weeks of the experiments, respectively. Analyzing the last weeks of the conducted experiments, it is conspicuous, that it was colder during the system experiment, although it was conducted in April and hence one month closer to summer. Comparing each first weeks, this is reversed, since here the April weather was a bit warmer than the March one. Another interesting observation holds the comparison between both weeks with the system installed. While during week one, the temperatures were higher, reaching a maximum of ca. 28°C. During the second week, the highest temperature only holds 18°C, which means a difference of 10°C regarding both

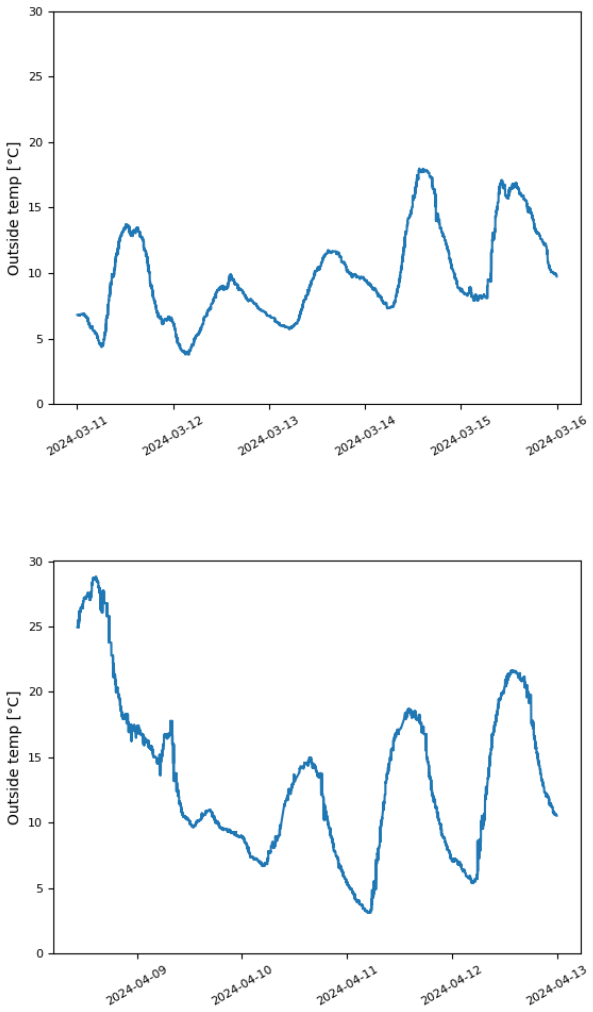


Figure 5.1: Temperature evolution of both experiment phases for their first week. Each plot shows data depicted in Celsius.

peaks. Further, each week one weather shows an upwards temperature evolution, but week one of the second phase has a high temperature drop at the beginning. First phase's week two seems to be rather consistent regarding weather temperature, while experiment stage two's second week shows a downwards trend.

5.3 Daily Energy Consumption

Figures 5.3, 5.4, 5.5 and 5.6 depict plots of the workstation's and both lamps' energy consumption over each experiment phase, two weeks without and two weeks with the proposed system.

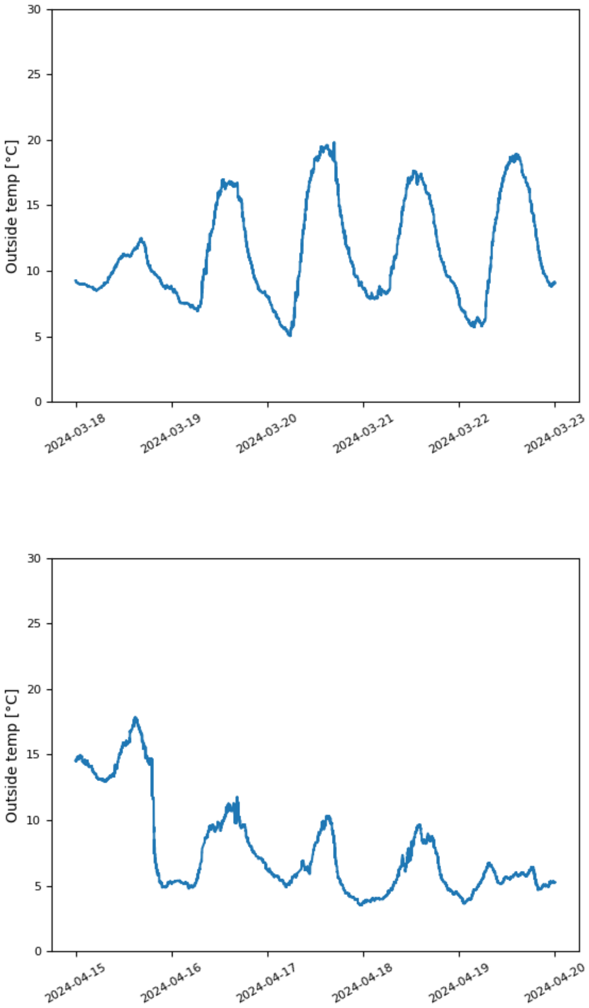
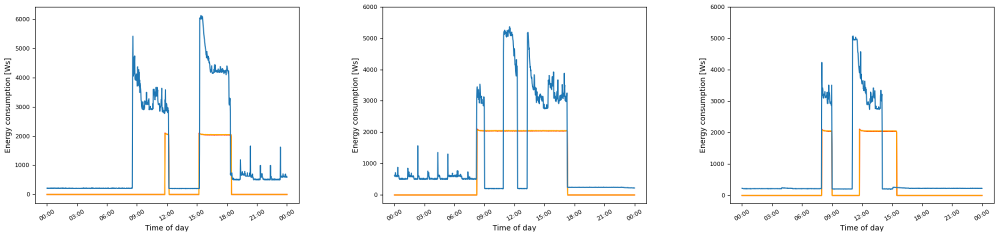


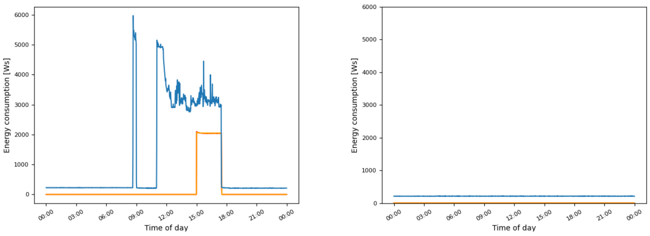
Figure 5.2: Temperature evolution of both experiment phases for their second week. Each plot shows data depicted in Celsius.

Firstly, the workstation energy consumption data, blue line in the plot, shows no peaks, meaning no energy was used these days. Another conspicuous behavior the graphs show, is that each peak of the workstation line starts on a higher point than it ends, the energy consumption decreases over time, before staying on a constant level. Furthermore, the plots depicting data points on workstation consumption retrieved with the system contain many short peaks with zero energy consumption in between. This is especially recognizable in the week one plots. Moreover, all figures show different patterns of workstation energy use, since peaks and valleys show no similarities in their evolution. For example, Fig. 5.4c shows a nearly consistent consumption through its peak, while e.g. Fig. 5.4b has several peaks separated by spots with low energy consumption.

Secondly, the lamp consumption plots can be analyzed. Those are depicted in the red and orange lines. The red line displays the ceiling lamp right next to the window and the orange graph data points for the neighboring lamp. For all four weeks in both phases, the graphs show, that both lamps



(a) $11^{th} March$ **(b)** $12^{th} March$ **(c)** $13^{th} March$



(d) $14^{th} March$ **(e)** $15^{th} March$

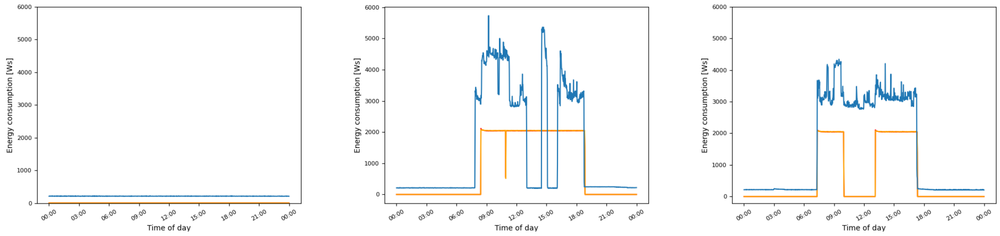
Figure 5.3: Energy consumption of workstation and lamps during the first week without the proposed system. Workstation power demand is depicted in blue, consumption of the lamp closest to the window in red and the neighboring lamp's consumption in orange.

are always turned on and off together, since the red line cannot be recognized in any plot, since it is identical with the orange line. Another noticeable observation is, that the lamps have a consistent, not fluctuating, power consumption, because they can be either turned on or off. The workstation is comparably significantly more fluctuating, since a laptop's power demand relies on the current executed tasks. Interesting is also the fluctuating energy consumption of the lamps between 10 and 12 am in Fig. 5.5c.

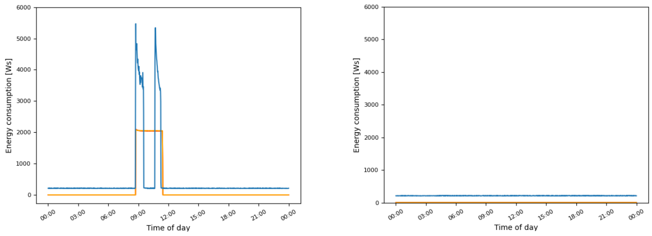
Comparing both, the lamp and workstation data lines in the plots, holds further interesting information. While it is worth mentioning, that the lamps are turned on every time the workstation is on during the second experiment stage, the baseline shows different data. On the one hand lights are sometimes turned on when no energy is consumed by the workstation, while on the other hand, lamps are turned off, when the desk devices demand power. Especially in between two workstation consumption peaks, the lights were often on, as for example seen in Figures 5.3b and 5.4b. Fig. 5.3c provides also an interesting plot, since the lamps were on in the afternoon, after the workstation consumption was already low. This probably shows, that the occupant forgot to turn off the lights before leaving the office and another person turned them off later. Scenarios like this do not occur with the proposed system, the lights are turned off every time in the afternoon with no delay compared to the workstation consumption.

5.4 Data on Thermostat States

The thermostat data depicted in Fig. 5.7 shows huge differences. As shown in the graph, during the baseline data acquisition, the thermostat valve was adjusted a few times resulting in some higher radiator heating phases. For example, at the first experiment's start, the thermostat was adjusted

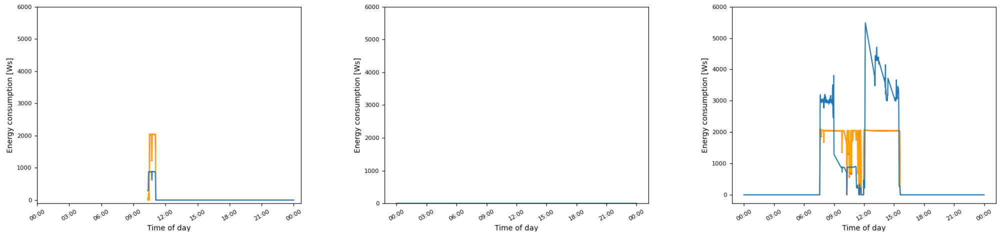


(a) $18^{th} March$ **(b)** $19^{th} March$ **(c)** $20^{th} March$

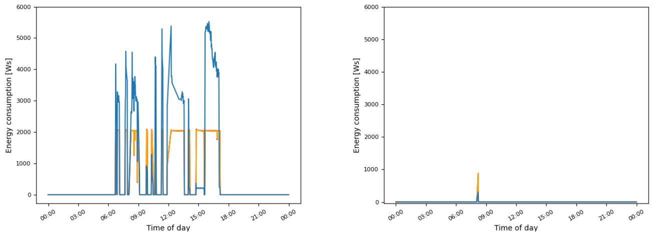


(d) $21^{st} March$ **(e)** $22^{nd} March$

Figure 5.4: Energy consumption of workstation and lamps during the second week without the proposed system. Workstation power demand is depicted in blue, consumption of the lamp closest to the window in red and the neighboring lamp's consumption in orange.

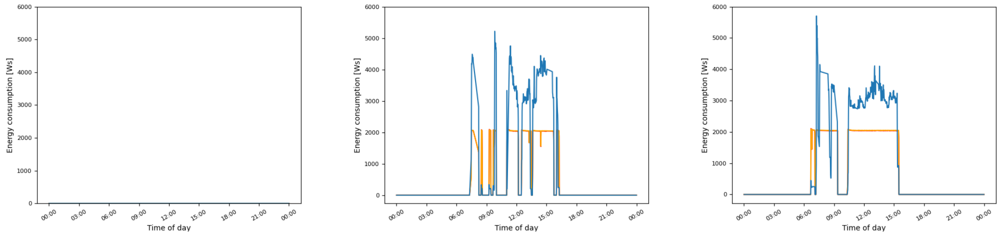


(a) $8^{th} April$ **(b)** $9^{th} April$ **(c)** $10^{th} April$

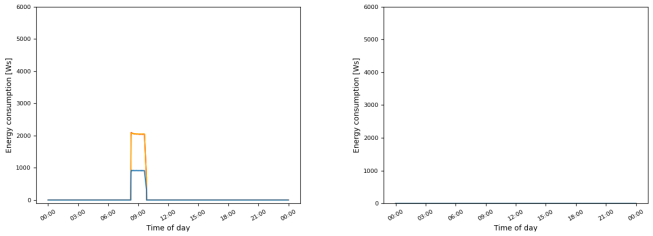


(d) $11^{th} April$ **(e)** $12^{th} April$

Figure 5.5: Energy consumption of workstation and lamps during the first week with the proposed system. Workstation power demand is depicted in blue, consumption of the lamp closest to the window in red and the neighboring lamp's consumption in orange.



(a) $15^{th}April$ **(b)** $16^{th}April$ **(c)** $17^{th}April$



(d) $18^{th}April$ **(e)** $19^{th}April$

Figure 5.6: Energy consumption of workstation and lamps during the second week with the proposed system. Workstation power demand is depicted in blue, consumption of the lamp closest to the window in red and the neighboring lamp's consumption in orange.

to a temperature of 20°C for the first three to four days and after a short interval, where it was turned into frost protection mode, meaning 7°C, the set-point temperature was set to ca. 14°C. After a little peak to again 20°C, the thermostat was adjusted to lower values before set to frost protection mode. The smart thermostat with a set-point temperature of 20°C only has four small peaks. The remaining time intervals sees the thermostat in "Off" mode, meaning frost protection state. Generally, it can be recognized, that the baseline heating energy consumption is higher than the system's.

5.5 Comparing manual and automated Consumption Data on the Workstation

Comparing gathered workstation consumption data with a simulated consumption on the respective days, shows, that energy could be saved in some intervals between the occupant enters in the morning and leaves in the afternoon. Fig. 5.8 therefore shows these simulated data in comparison with retrieved power consumption information for the four days of occupant presence and activity during the experiments with the deployed system. Especially on the plotted data for the 11^{th} and 16^{th} April, the energy demand had been reduced by deploying the system. While some small savings could be made by turning off the plugs for short intervals in few minutes ranges, a larger amount of energy is saved in longer time intervals lasting for about an hour or more.

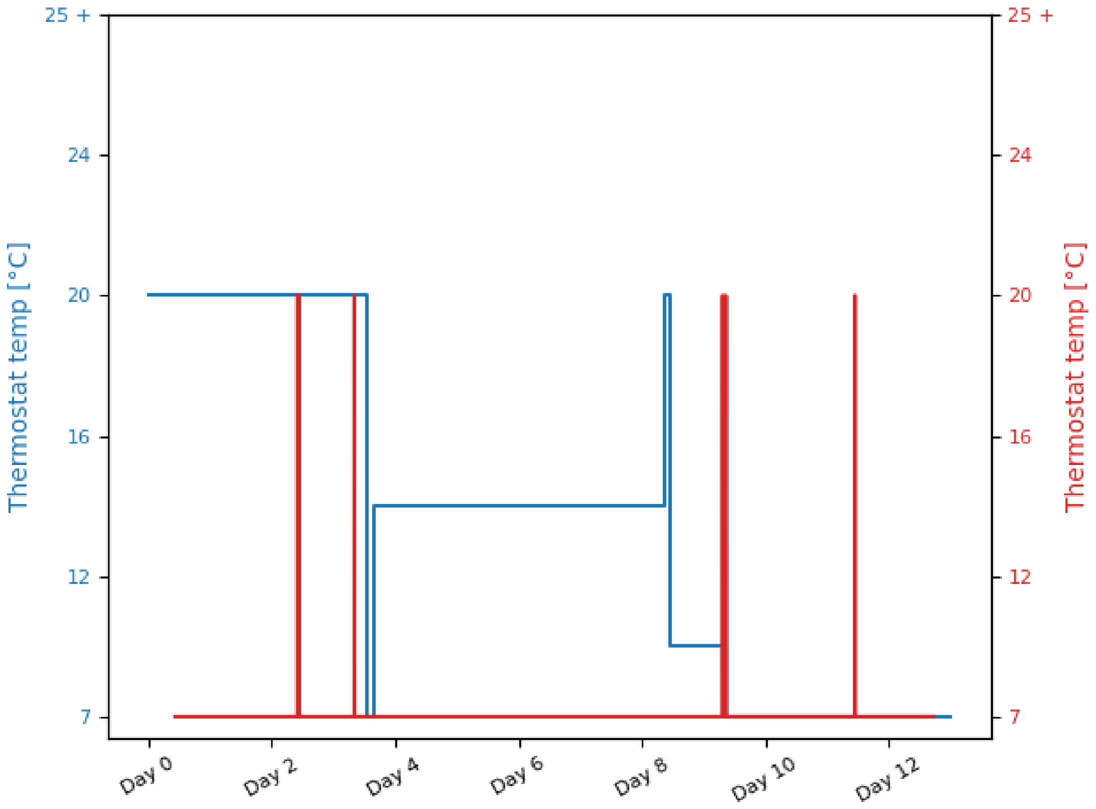
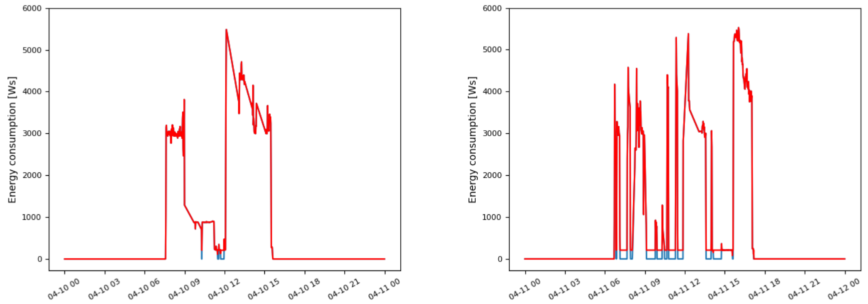


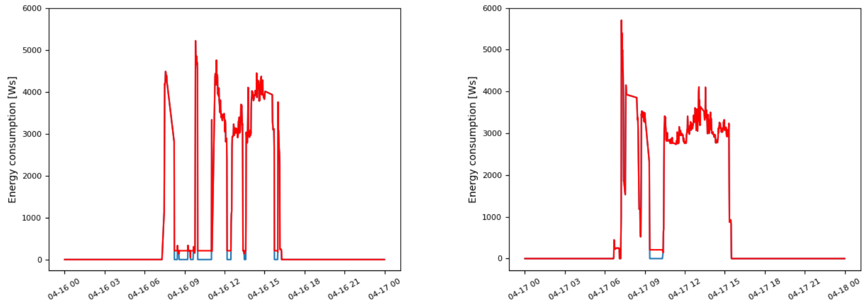
Figure 5.7: Thermostat data of both experiment stages compared, with the baseline experiment phase depicted in blue and the system's thermostat data in red. Additionally, the baseline thermostat levels are converted to set-point temperatures according to "How to set a thermostat" by the Heinrich-Heine-Universität Düsseldorf [hhu22].

5.6 Analyzing Lights Data

Comparing different illuminance levels to the light power consumption, as depicted by Figure 5.9, shows some insights on lamp control. The graphs display measured illuminance values in blue and light consumption measurements in red. Only one lamp's data is used to plot this graph, because they are both controlled synchronously, as it is explained before. As shown, the illuminance values did mostly not rise above 200 Lux. There is only one extreme outlier on first week's Wednesday, where it reaches over 1000 Lux for a moment. Furthermore, it is recognizable, especially in the week two plot, that the light control works, since the lights are turned on, when the illuminance is below the deployed 250 Lux. Therefore, as shown in the graph, the illuminance level increases, meaning the lamps are indeed turned on. Both lights are also not turned on every time, when the illuminance reading is below the mentioned threshold. This is due to no present occupant. Since both Figures show, that the illuminance increases when the lamps are turned on and decreases otherwise, it is assumed, that the system works how it is supposed to.

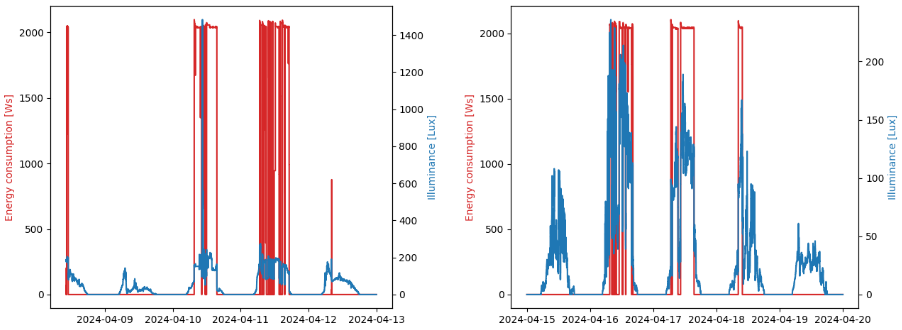


(a) $10^{th}April$ **(b)** $11^{th}April$



(c) $16^{th}April$ **(d)** $17^{th}April$

Figure 5.8: Desk energy consumption for working days under control of the proposed system, blue line, compared to simulated energy demands with manual control by the occupant, red line, for the presented days. This is calculated under the presumption, that the office user turns on the desk workstation when entering in the morning and off when leaving in the afternoon. Accordingly, data is only compared from start to finish of the work days.



(a) Week 1 **(b)** Week 2

Figure 5.9: Comparison between illuminance levels and lamp energy consumption. The blue lines are illuminance readings and the red lines show lamp consumption data.

Average consumption	03/11	03/12	03/13	03/14	03/19	03/20	03/21	Average
Workstation [kWh]	0.046	0.042	0.039	0.045	0.048	0.053	0.038	0.044
Lamps [kWh]	0.026	0.068	0.038	0.02	0.064	0.047	0.067	0.047

Table 5.1: Average hourly consumption on working days during test stage without the proposed system.

Average consumption	04/10	04/11	04/16	04/17	Average
Workstation [kWh]	0.034	0.023	0.029	0.038	0.031
Lamps [kWh]	0.059	0.032	0.038	0.056	0.046

Table 5.2: Average hourly consumption on working days during test stage with the proposed system.

5.7 Comparison on Average Consumption Data

Comparing average consumption data can yield interesting information on potential energy savings. Therefore, Table 5.1 displays hourly average consumption data in kilowatt-hours on working days, i.e. the occupant's present days, during the test stage without the deployed system. As shown in the provided table, hourly average consumption of the workstation is rather consistent, with energy demands between 0.039 kWh and 0.053 kWh. On the opposite, depicted data points for light consumption are varying between 0.02 kWh and 0.068 kWh, resulting in larger daily fluctuation. To compare this information with identically retrieved data for the test phase with deployed system, Table 5.2 depicts the respective data gathered in phase two of the experiments. It is recognizable, that the workstation energy consumption is similar consistent, showing a difference from highest to lowest of 0.015 kWh. On the other hand, the respective minimum and maximum hourly average consumption is 0.023 kWh and 0.038 kWh, which is clearly lower than the related values during the first test phase, also resulting in an average hourly consumption of 0.031 kWh compared to 0.044 kWh. The ceiling lamps energy demands are more consistent with the system, but can't show any energy reductions compared to manual control, with the respective averages figuring 0.047 kWh and 0.046 kWh consumption.

6 Discussion

Firstly, evaluating the described results on the respective thermostat temperatures must be done under comparison of different weather conditions, especially regarding outside temperatures. Comparing both thermostat plots in Fig. 5.7 shows therefore a drastically lower heating energy demand with the proposed system. Differences mainly result from the first weeks of both stages though. Relating these assumptions to the respective outdoor temperature plots in Fig. 5.1, shows, that the week one data in April shows generally higher temperatures and thus reduces the smart thermostat's impact. Nevertheless, it can be assumed, that not all of the saved heating energy rely on this fact, since the differences are rather huge. Another reason explaining this behavior could be, that the thermostat's initial temperature set-point was set to 20°C and thus may not be the desired room temperature of the occupant. Contradictory, the base thermostat's highest set-point in the baseline acquisition was 20°C and therefore not higher. The system also provides the possibility to change the target temperature by adjusting the thermostat on button click and additionally using the command line interface to re-adjust the target temperature. This makes the discussed justification on the system's thermostat performance obsolete.

Comparing week two thermostat data in Fig. 5.7 with respect to week two's outdoor temperatures depicted in Fig. 5.2 gains further insights on possible energy savings with the use of a smart thermostat. While both set-point thermostat plots show short peaks on 20°C , although the baseline starts week two on a set-point temperature of about 14°C, meaning the heating costs are thus also higher when the system is not used. This result becomes even more meaningful comparing both week's outside temperatures. These show warmer weather conditions for data gathered in March and therefore during the first experiment stage.

Nevertheless, comparing the thermostat data shows, that heating energy could be handled more efficiently due to simply turning off the radiator with a smart thermostat on weekends and outside working hours, which itself are simply tracked via the motion detector. For example, the thermostat plots in Fig. 5.7 shows this effectiveness on comparison of the weekends separating both stages weeks. While the radiator heats the room to a set-point temperature of 14°C during the first weekend, the proposed system reduces this energy demand by 100% by turning off the heating due to absence of occupants.

Comparing energy consumption data on all electric controlled devices has to be conducted in respect to a lack of data, since the office was only used on four days in the two experiment weeks. This is reasoned in illnesses of the occupant and external appointments, that do not demand the occupant's presence in the office. Small hills in plot 5.5a, 5.5e and 5.4a are the only exceptions to otherwise zero energy consumption on absence days. While the first peak in week one probably results from first data points right after deploying and starting the proposed system, the other hills are probably related to persons walking through the room, since the office is connected directly to three other rooms and therefore recognizes different persons walking through the office sometimes. Hiding these little hills of small energy consumption makes the data consistent in its energy demands with no present occupant, hence the plots show a 0 Ws line through absence times.

Comparing all energy consumption plots shows, that there can not be determined any repeating patter. This is due to the office occupant having different schedules every day and also working from home on some days, which makes it especially hard to compare data directly day to day. The fact of gathering seven days of presence during the first test stage compared to only four in the second phase strengthens this difficulty. So, in order to gain ability on avoiding these problems, the plots in Fig. 5.8 show a comparison of the data conducted during stage two and simulated baseline data for the specific days. Simulations were done based on the conducted occupant interviews. Accordingly, the data shows small energy savings every time no presence is tracked during work time, since the system stops any kind of energy consumption, while the occupant is not present in the office. This was not done before the proposed system's deployment. Though these energy demands are rather low due to the laptop being disconnected and the monitors going to sleep mode, some energy savings are still achieved with the proposed system on this comparison base.

Lastly, examining direct comparison between both test stages need to retrieve other figures according to the named reasons. This objective is achieved with the hourly average consumption data in Tables 5.1 and 5.2. Although the values seem to show no significant improvement on automatic light control compared to manually switching lights on and off, energy could be handled more efficiently with the proposed system regarding workstation consumption. The average dropping about 0.013 kWh per hour, results in savings of 0.104 kWh in an eight hour working time. Enhancing this value to a week of five days leads to 0.52 kWh saved. Further examination on a yearly level results in 22.36 kWh, assuming 43 working weeks a year. Beyond that, comparing the lamps' average energy consumption in more detail, holds promising results according to energy savings, because the similar average consumption in both experiment phases need to be further evaluated. Even though both lamps were on every time the occupant was present in the room during the second experiment phase, the hourly average consumption was not higher compared to the baseline data. This is reasoned in the system turning off the lamps even on small intervals of occupant absence, while the lights were often kept on in short intervals during the baseline data acquisition. So, while turning on the lamps every time the occupant is present, the system's energy consumption is similar to the baseline's. It can also be added, that the occupant might have not turned on the lights every time while working, due to not needing the 500 Lux recommended for office lighting [len24]. Even though this table provides promising values on energy saving with the proposed system, it has to be considered carefully due to the before mentioned comparability issues, different number of days and some small lacks in the system data points. Since the first mentioned problem is already explained, the second difficulty results from comparing seven days data to four days data, which might as well create differences due to more days result in more representative information. Therefore, the four days of experiment phase two are potentially lucky days with a generally lower energy consumption due to external meetings etc. The last mentioned problem in the depicted data follows from some small device and application lags, leading to delays of sometimes up to half an hour in the deployed system's data points. In addition, receiving no response on requesting sensor readings, especially for the plugs measuring power consumption, is handled by simply ignoring possible values. Thus reduces the amount of data points and therefore the accuracy.

6.1 Findings

The Research question proposed at the beginning of this work can be answered with promising results. As examined before, simple, low cost and smart environments, as the one proposed in this thesis, can reduce office carbon footprint by 22.36 kWh a year, assuming environmental friendly behavior on manual occupant control. Taking this savings into account to reduce carbon footprint, results in nearly 8.6 kg CO_2 reduction per office in a year, based on Germany's power sector producing 385 grams of the greenhouse gas per generated kilowatt-hour [Tis23]. Determining potential financial benefits out of the achieved energy reductions shows savings of 5.92€ assuming electricity costs of 26.50 Cent per kilowatt-hour in Germany [Fec24]. These ca. 6€ of savings seem rather low at first, but considering saving a few euros per office and year results in more significant savings. For example, assuming 100 offices, financial benefits would increase to ca. 600€. Assuming 100 offices would also lead to 860 kg less CO_2 per year. As shown on comparison of the thermostat data, further energy can be saved by automatically control thermostats.

Evaluating sub-question one shows, that possibilities to acquire data are plugs, that can be plugged into power sockets in front of devices to measure the devices energy consumption. To retrieve information on thermostat data, it is possible to gather data through manual appending files, as done to gain baseline information, and to get thermostat modes when using smart thermostats.

Answering the second sub-question about the architecture of a simple system results in two Python scripts retrieving and storing data for the Z-Wave and Zigbee devices. So implementing needed technologies in different scripts can be enough to control an office room. This architecture makes it also simple to separate respective networks and does not result in interference of multiple scripts trying to access one USB-port for network communication.

Lastly, the third sub-question can be answered with this work's data handling. Using online databases makes it easy to access data points remotely with no need to be present at the installation premise. Data therefore could be gathered in one minute intervals, making rather granular evaluations possible but also can be used to examine long term information. Retrieved data can be compared according to simply plotting measured values to get a general overview, but can also be converted to average consumption data to gain more precise insights on energy savings. This especially makes it easier to compare multiple data in similar office settings, since occupant behaviors might make it difficult to just compare day to day data. This is due to office occupants having different schedules each day or might work from the home office on some days.

6.2 Lessons Learned

This section examines occurred obstacles and learned lessons from facing these obstacles. It is therefore separated in organizational and implementation obstacles.

6.2.1 Organizational Obstacles

For the organizational obstacles, the only obstacle faced happened on trying to install the system in the premise. In order to keep the system's expenses as low as possible, the installation plan listed only Plugwise plugs to control the two ceiling lamps. Therefore, electric sockets and plugs had to be mounted in between the cable powering respective ceiling lamps. This normally needs an electrician to conduct these measures. On help from the office's occupant, contact to the "Technische Leitware Stadtmitte" was established. Nevertheless, the installation by an electrician was not applicable due to timing and cost. After discussions between Prof. Dr. Marco Aiello, Dr. Ilche Georgievski, Dr. Felix Hebeler and the author, it was decided, that Dr. Hebeler would install the sockets and plugs.

6.2.2 Implementation Obstacles

During the implementation of the system with respective technologies and devices, some more obstacles had to be faced. In addition to general small problems with some devices, like small bugs, installing needed Python libraries for the openzwave-python library to control Z-Wave devices lead to some problems on the Raspberry Pi. On trying to build the needed repository as a library, errors were thrown. As trying to readjust the code based on the error messages a few times, the library could not be built either. After some further research and trying to install dependencies manually and the needed library from git source, it worked and the openzwave library could be installed successfully.

Another problem occurred during implementation was recognized on trying to use a GrovePi+ board on the Raspberry Pi to connect an illuminance sensor to it, that could have read light values right from the desk and therefore more accurate and easier to handle. The problem occurred due to the Server had installed Raspbian OS version Bullseye and not Buster. After downgrading the OS version to buster and further reinstall all dependencies, the next problem occurred, since buster devices should not be connected the university's eduroam network according to TIK. The eduroam connection though was essential to store data to the online InfluxDB database. This lead to an installation plan adjustment, which specifically means, that illuminance readings were gathered from the multi-sensor instead of the Grove Pi sensor. Therefore the OS could be re-upgraded to Bullseye and connected to the internet via eduroam. This decision was made under consultation with the supervisor Dr. Ilche Georgievski and according to being able to gather illuminance environment readings with the multi-sensor. Since the multi-sensor had another position in the room, the light thresholds had to be adjusted accordingly. The fact of the lights being turned on the whole time during presence might also be according to this circumstance and not completely correct configured thresholds.

According to feedback from the office occupant, a minor change was included in the system's code during the second experiment stage. The occupant reported annoying workstation turn offs while still working. First, the duration, where the motion sensor sends a no-motion-detected signal, if no movements were detected, was increased from four to six minutes. Since this adjustment did not fix the turn offs completely, but only made them more rare, an additional check on the current power consumption was incorporated. Hence, the workstation from there one got turned off only if no occupant presence was tracked and the workstation consumption was below a threshold measured on setting the desk devices to sleep mode. This system improvement removed the annoying factor reported from the occupant without increasing the energy consumption. So, the data could be evaluated anyway.

Two last small obstacles are both connected to the used thermostat. Firstly, energy consumption of the smart thermostat was rather high, since the batteries supplying power to the device were empty after one week. Changing the batteries and re-adapting the thermostat resolved this problem for one week again, but did not remove it. Therefore, a small adjustment was made after acquisition of the data to try avoid emptying the batteries that fast. Whether these changes lead to the wanted effect or not is unknown until now, since the changes were incorporated less than a week before the submission date of this work. The other mentioned obstacle regarding the thermostat resulted from bad Danfoss adapters included in the thermostat's package. Since the old thermostat connection was a Danfoss RAVL standard one, the corresponding adapter was used, but it was not easy to mount the thermostat on the radiator valve. With a lot of trying and the help of Dr. Hebeler, it was possible to mount the thermostat on the valve though.

7 Conclusion and Outlook

Following the discussion on the presented results shows, that enhancements in terms of energy savings could still be made through controlling office devices by an automated system compared to manually control by environmentally friendly occupant behavior. Therefore, the research question opening this thesis can be answered positively. Especially assuming not every university office is used by environmentally friendly occupants as in the experiment premise of this work, deploying similar smart environments in multiple university offices could help to save a significant amount of energy and with that also money. Extending smart technologies further to lecture rooms, laboratories and hallways could additionally add impacts on energy savings. Controlling devices with smart systems additionally makes the devices' energy consumption more independent from personal occupant behavior.

To conclude this thesis, it is specifically worth mentioning, that improvements in reducing heating energy consumption could be easily achieved with simple and smart thermostat technologies, since occupants mostly do not remember turning off the thermostat before leaving, thus keeps the room heated. Especially in winter, automatically turning off the thermostat when office occupants leave, can provide big impacts on reducing energy demands.

Providing an outlook to possible future work, further data acquisition with the proposed system could be conducted in order to gain more knowledge on respective savings and examine further evaluations. This could, for example, reduce the lack of data during the second experiment stage due to the occupant not being present in the office on many days, thus leaving only four days of data to evaluate. The mentioned outlook could be additionally enhanced by making some tuning of respective thresholds, for example to the light ones. Therefore, it could also be considered to use further sensors, e.g. one to gather illuminance readings directly on the workstation, which would make it easier to control the lights more accurately.

Furthermore similar systems could be installed in more premises around the university to gather further insights on possible enhancements in energy efficiency. This yields as well for additional office environments, but also for other buildings and rooms like hallways, laboratories or lecture rooms. Especially during planning and building processes of new buildings, it could be considered to immediately install smart systems to avoid re-investing and therefore improve the climate footprint and increase financial benefits.

In addition, more complex sensors could be used to track different settings in the premise faster and more precisely. For example installing some pressure sensor on the desk chair could maybe give information on an occupant leaving the desk. Therefore, the workstation could be turned off more precisely and faster, resulting in more energy savings. Nevertheless, this would become even more complicated, when the workstation or desk is height adjustable and thus enables the occupant to work while standing.

Acknowledgments

The author would like to thank Prof. Dr. Marco Aiello for providing the thesis and helpful advice. Furthermore, the author thanks Dr. Ilche Georgievski for supervising the thesis, obtaining the needed devices and useful suggestions. Special thanks go also to Dr. Felix Hebeler for providing his office, insights on his working behavior, helpful advice and installation help. Additionally, the author would like to thank the whole rector's office team for their constructive help and for access to the building and office. The author would also like to thank Mr. Nasiru Aboki and Ms. Ebaa Alnazer for lending devices.

Bibliography

[ABS19] S. Ahmadi-Karvigh, B. Becerik-Gerber, L. Soibelman. “Intelligent adaptive automation: A framework for an activity-driven and user-centered building automation”. In: *Energy and Buildings* 188-189 (2019), pp. 184–199. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2019.02.007. URL: https://www.sciencedirect.com/science/article/pii/S0378778818327063 (cit. on p. 17).

[AGBS18] S. Ahmadi-Karvigh, A. Ghahramani, B. Becerik-Gerber, L. Soibelman. “Real-time activity recognition for energy efficiency in buildings”. In: *Applied Energy* 211 (2018), pp. 146–160. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2017.11.055. URL: https://www.sciencedirect.com/science/article/pii/S0306261917316409 (cit. on p. 17).

[All] C. S. Alliance. *Zigbee: The Full-Stack Solution for All Smart Devices*. URL: https://csa-iot.org/all-solutions/zigbee/ (visited on 04/18/2024) (cit. on p. 28).

[CM10] L. Chiaraviglio, M. Mellia. “PoliSave: Efficient power management of Campus PCs”. In: *SoftCOM 2010, 18th International Conference on Software, Telecommunications and Computer Networks*. 2010, pp. 82–87 (cit. on p. 18).

[EB15] F. M. for Economic Affairs, E. (BMWi). *Energy Efficiency Strategy for Buildings*. 2015. URL: https://www.bmwk.de/Redaktion/EN/Publikationen/energy-efficiency-strategy-buildings.pdf?__blob=publicationFile&v (visited on 04/22/2024) (cit. on p. 13).

[EU19] E. U. (EU). *The European Green Deal*. 2019. URL: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (visited on 04/22/2024) (cit. on p. 14).

[EU24] E. U. (EU). *Causes of climate change*. 2024. URL: https://climate.ec.europa.eu/climate-change/causes-climate-change_en (visited on 04/11/2024) (cit. on p. 13).

[Fec24] K. Fechner. *Strompreise 04/2024: Das kostet Strom aktuell in Deutschland*. 2024. URL: https://www.vergleich.de/strompreise.html (visited on 04/28/2024) (cit. on p. 45).

[GNN+17] I. Georgievski, T. A. Nguyen, F. Nizamic, B. Setz, A. Lazovik, M. Aiello. “Planning meets activity recognition: Service coordination for intelligent buildings”. In: *Pervasive and Mobile Computing* 38 (2017), pp. 110–139. ISSN: 1574-1192. DOI: https://doi.org/10.1016/j.pmcj.2017.02.008. URL: https://www.sciencedirect.com/science/article/pii/S1574119217301050 (cit. on p. 17).

[HH08] R. K. Harle, A. Hopper. “The potential for location-aware power management”. In: *Proceedings of the 10th International Conference on Ubiquitous Computing*. UbiComp ’08. Seoul, Korea: Association for Computing Machinery, 2008, pp. 302–311. ISBN: 9781605581361. DOI: 10.1145/1409635.1409676. URL: https://doi.org/10.1145/1409635.1409676 (cit. on p. 18).

[hhu22] hhu. *How to set a thermostat*. 2022. URL: https://www.hcsd.hhu.de/en/energy/translate-to-english-detailansicht-energie/kinderleicht-wie-ein-thermostat-funktioniert-1 (visited on 04/25/2024) (cit. on p. 39).

[IEA23] I. E. A. (IEA). *Tracking Buildings*. 2023. URL: https://www.iea.org/energy-system/buildings (visited on 04/22/2024) (cit. on p. 14).

[len24] lendis. *Lighting in the office*. 2024. URL: https://www.lendis.io/en/guide/arbeitsschutz/lighting/ (visited on 04/29/2024) (cit. on pp. 30, 44).

[MQT] MQTT.org. *MQTT: The Standard for IoT Messaging*. URL: https://mqtt.org/ (visited on 04/18/2024) (cit. on p. 28).

[Nat24] U. Nations. *Causes and Effects of Climate Change*. 2024. URL: https://www.un.org/en/climatechange/science/causes-effects-climate-change (visited on 04/11/2024) (cit. on p. 13).

[PAN19] V. Pujani, F. Akbar, R. Nazir. “Management Review of Energy Consumption: The Energy Saving Opportunity in University Buildings”. In: *Proceedings of the 5th International Conference on Industrial and Business Engineering*. ICIBE ’19. Hong Kong, Hong Kong: Association for Computing Machinery, 2019, pp. 110–116. ISBN: 9781450376532. DOI: 10.1145/3364335.3364390. URL: https://doi.org/10.1145/3364335.3364390 (cit. on p. 18).

[Ros17] L. Rosencrance. *Definition Zigbee*. 2017. URL: https://www.techtarget.com/iotagenda/definition/ZigBee (visited on 04/18/2024) (cit. on p. 28).

[RRR20] H. Ritchie, P. Rosado, M. Roser. *Breakdown of carbon dioxide, methane and nitrous oxide emissions by sector*. 2020. URL: https://ourworldindata.org/emissions-by-sector (visited on 04/11/2024) (cit. on p. 13).

[RRR23] H. Ritchie, P. Rosado, M. Roser. *CO2 and Greenhouse Gas Emissions*. 2023. URL: https://ourworldindata.org/co2-and-greenhouse-gas-emissions (visited on 04/11/2024) (cit. on p. 13).

[SGM20] A. Salosin, O. Gamayunova, A. Mottaeva. “The effectiveness of the Smart Office system”. In: *Journal of Physics: Conference Series* 1614.1 (Aug. 2020), p. 012028. DOI: 10.1088/1742-6596/1614/1/012028. URL: https://dx.doi.org/10.1088/1742-6596/1614/1/012028 (cit. on p. 17).

[SH17] K. Sun, T. Hong. “A simulation approach to estimate energy savings potential of occupant behavior measures”. In: *Energy and Buildings* 136 (2017), pp. 43–62. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2016.12.010. URL: https://www.sciencedirect.com/science/article/pii/S0378778816317716 (cit. on p. 14).

[Stu] U. of Stuttgart. *Saving energy together: Information from the University of Stuttgart*. URL: https://www.uni-stuttgart.de/en/university/profile/sustainability/energy/saving/ (visited on 04/22/2024) (cit. on p. 14).

[Tis23] I. Tiseo. *Carbon intensity of the power sector in Germany from 2000 to 2022*. 2023. URL: https://www.statista.com/statistics/1290224/carbon-intensity-power-sector-germany/ (visited on 04/28/2024) (cit. on p. 45).

[V24] A. B. V. *What is Z-Wave? Learn More About this Powerful Smart Home Technology.* 2024. URL: `https://homey.app/en-us/wiki/what-is-z-wave/` (visited on 04/18/2024) (cit. on p. 29).

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

place, date, signature