Office energy saving potential through component based automation, a design and implementation

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Abstract

One of the focus points of the University of Groningen in teaching and research is energy and sustainability. In 2012 two PhD students from the Distributed Systems research group proposed a prizewinning plan to make the Bernoulliborg building sustainable in terms of waste disposal and the use of water and energy. The proposed plan is being executed in the course of the year 2013. This thesis is part of the execution of the plan's energy savings solution that aims to save at least 7.7% (107,514 kWh) annually through automatically controlling HVAC systems, lights, computers, appliances, and providing energy consumption tracking.

A new automated system had been designed and installed in the north wing on the fifth floor of the Bernoulliborg building that is capable of monitoring and influencing the energy consumption of the offices and common areas. Plugwise devices have been installed, after considering multiple sensors and actuators, to monitor the energy consumption of devices and to turn them on or off. A computer client has been developed that acts as an activity sensor and provides the system with the ability to safely shut down computers or to put them into a standby mode. The installed system consists out of multiple loosely coupled software components that each fulfill their own dedicated tasks. Kafka has been chosen as the message queue by which the components communicate with each other through JSON messages. A ZooKeeper instance is used to monitor the state of components and provide automatic discoverability for all the components, including the Kafka message queue.

Based on the actual measured energy consumption data and the functionality of the created Green Mind system a simulated result was formed for the energy saving potential of the design. The biggest energy saving potential is the office and hallway lighting which, even on a bright sunny day, consumes multiple kilowatt hours per day. Computers use around one kilowatt hour per week per computer outside office hours, even when turned off. Through a smart set of rules the Green Mind system is capable of saving that energy by automating the control of the devices.

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Chapter 1

Introduction

This chapter introduces the background and research goals for this thesis about potential energy saving in offices through the use of a component based building automation system.

First, in Section 1.1, the context of the research domain is provided in order to create a better understanding of the origin and the reasons for this research. After clarifying the domain, the hypothesis and research goals are given in Section 1.2 along with a summary of the used approach and expectations. Finally, in Section 1.3, the relevance and contributions of this thesis are listed before giving an overview of the further structure of this thesis in Section 1.4.

1.1 Context

This thesis is conducted as part of multiple research projects, related to energy and sustainability, at the Distributed Systems research group at the University of Groningen. Energy and sustainability is one of the focus points in teaching and research of the university [3].

In 2012 Tuan Anh Nguyen and Faris Nizamic, two PhD students from the Distributed Systems research group, proposed a prizewinning plan [1] to make the Bernoulliborg building sustainable in terms of waste disposal and the use of water and energy. Winning the Green Mind Award [2] means that the proposed plan is being executed in the course of the year 2013. This thesis is part of the execution of the plan's energy savings solution that aims to save at least 7.7% (107,514 kWh) annually through automatically controlling heating, ventilation, and air condition (HVAC) systems, lights, appliances, and providing energy consumption tracking. HVAC systems are applied to control the indoor environment comfort (e.g., room temperature and ventilation).

Figure 1.1: The Bernoulliborg building.

The Bernoulliborg is located on the Zernike Complex in the Dutch city Groningen and was officially opened in February 2008. It accommodates 350 staff members and 500 students. The overall size is 33 by 83 meters and a height of 27 meters. It houses both the Faculty of Mathematics and the Faculty Natural Sciences as well as the departments of mathematics, computing sciences and artificial intelligence. Figure 1.1 shows the facade of the building. Common areas such as a library, cafeteria and lecture rooms are located on the two lower levels. Offices are located in three separate wings on the three upper floors of the building.

In order to reach the proposed minimal energy consumption saving of 7.7% a system has to be designed that can alter the state of devices such that energy can be saved without the loss of comfort or drastic alterations to the building's structure. A building management system (BMS) is already present in the building, which is accessible remotely by the campus management. BMS systems are widely used in buildings to control and monitor the electrical equipment of the building, such as lighting and HVAC systems. However, the BMS located at the Bernoulliborg building is limited to controlling electrical equipment on a building level. The only segmentation in the system is at most on a 'per wing' basis, which is nowhere near the envisioned granularity of management on a 'per person' or 'per room' level. The control of the BMS is limited and not easily accessible by third party software, it was thus not integrated into the design of the new system.

Due to the limitations of the BMS it is necessary to install new sensors and actuators so that it becomes clear what, or who, uses the most energy and to measure how much exactly is being consumed at what time. These sensors and actuators also use energy but need to create enough energy savings to justify their costs. A live experiment was created to monitor eight actively used offices, located on the fifth floor in the north wing (the leftmost wing in the picture of Figure 1), in order to measure energy consumption, test the possible sensors, determine their usefulness, and gain knowledge about the interaction of office workers. Along with the offices the experiment also includes the adjoining hallway, meeting room, toilets and kitchen/communal area.

The plan proposed for the Green Mind Award encompasses more than just energy saving and the system in this thesis thus takes into account the other components that will be integrated with the system over time.

1.2 Research goals

First, in Subsection 1.2.1, the hypothesis for this thesis is provided. In order to narrow down the scope a fixed number of research goals have been set. This section describes those goals in Subsection 1.2.2, as well as the plan to reach those goals in Subsection 1.2.3 and the initial expectations about the outcome of the thesis in Subsection 1.2.4.

1.2.1 Hypothesis

The purpose of this experiment is to design and build an actual working system that is capable of automating energy consumption management in regular offices that are being used by employees. Previous research [4] has indicated that energy can be saved by implementing such automated systems but are usually limited to a small scale implementation in a controlled environment. The ever growing amount and implementations of sensors and the connectivity of such devices make it possible to implement such a system in a working environment, outside of a lab setup.

By implementing the system in an uncontrolled environment of actively used offices, it will presumably be less stable due to users tampering with the sensors out of curiosity or inexperience. It also raises the case that no office worker is alike, which means the amount of potential energy saving will differ from office to office. It will therefore be of use to find out if an automated system will scale up to a larger and more volatile operating environment. The system should not lose too much of its effectiveness in order to save energy while justifying the costs, both in money and energy consumption of the system itself, and the effort required of installing such a system in an existing or new building.

Based on previous research, discussions with building managers, and observations during walkarounds in the Bernoulliborg the potentials of saving energy are high and the system should be able to save energy even if the scale and volatile environment lower the efficiency of the system. The hypothesis is thus as follows:

'Installing a building automation system that controls multiple occupied offices has the potential to save energy.'

1.2.2 Measurable goals

A total of three goals have been set in order to judge the effectiveness of the final implementation. The details of these goals are described in this subsection and will be used in the discussion of the estimated results and the conclusion of this thesis later on.

Goal 1 - Lighting
Based on the goal set by the proposed plan for the Green Mind Award: the energy consumption of lighting should be *lowered by 25%*. Lighting is currently motion enabled or always on, which is not very efficient.

Goal 2 - Electronic devices
Based on the goal set by the proposed plan for the Green Mind Award: the energy consumption of electronic devices should be *lowered by 25%.* Non-essential devices sometimes remain enabled unnecessarily (e.g., during absence, night, or weekend).

Goal 3 - Return on investment
Based on the goal set by the proposed plan for the Green Mind Award: costs of installation should be *returned within 7 years* at most. Savings should be high enough to make the purchase and installation of such a device appealing.

1.2.3 Planned solution

In order to reach the envisioned goals, an automated system needs to be able to influence the energy consumption of lights and electronic devices in the existing offices. The system also needs to collect the consumption information of the individual devices for research purposes and to create user awareness to encourage even more energy savings by the users themselves.

The plan is to reach the goals by installing remotely accessible sensors and actuators in the offices to provide an automated system with all the necessary data to base decisions on and to make it possible to set non-essential devices in standby mode or to turn them off completely. The governing system itself consists of multiple subcomponents. Each component performs different tasks and has their own dedicated goal (e.g., collecting the consumption measurements). Components work together to reach their common goal, reducing the energy consumption in the offices, and to share useful information with the other components so that both the raw sensor data and other processed information is accessible to each component. To make the management of these components easier, the components communicate either through a REST interface or a message queue, which allows for loose coupling between the components. REST is the dominant web application programming interface (API) that is usually described in the context of HTTP, whereas message queues are separate software components that can be used for asynchronous communication where messages are placed onto a queue until the recipient receives them. The data is stored in a central database and components find each other through ZooKeeper, an open-source server which enables highly reliable distributed coordination.

It is envisioned that over time new sensors and actuators are added to the system, as well as new components that provide better or completely new functionality, so that the system keeps updating and improving. The system is named the Green Mind system which refers to its origin as a proposal for the Green Mind Award.

1.2.4 Expectation

Through the loose coupling of the individual components the system should scale better, more easily adapt to new components, and be easier to manage than a conventional BMS. By using a dynamic combination of small hardware, that integrates with the existing building design, and dedicated software the system has the potential to save energy at a relatively low cost without the loss of comfort and even the potential to increase comfort. Based on previous local projects and preliminary research the initial design of the system should be able to reach the goals of this thesis while also forming the basic framework for future research.

1.3 Contributions

The main driver behind this project is the focus of the university on energy and sustainability and also the implementation of the winning plan of the Green Mind Award. Through this thesis a framework is built that presents a multitude of new research possibilities for bachelor and master thesis projects, such as research into energy awareness amongst employees, as well as allowing the university to design and develop new 'homegrown' ideas, a desire expressed in the original call for submissions for the Green Mind Awards [5]. Accessibility to a live testing environment of actively used offices is something that is rarely done before and gives the University of Groningen an edge over other universities which they can use as a selling point.

Other research focuses on measuring and influencing devices in a controlled environment and point out that there is energy to be saved through smart automated management. This project aims to determine if such solutions are still manageable and efficient in a larger and more volatile environment. Another point of focus is to create a system that is setup in such a manner that it is applicable to multiple buildings. Not just another prototype but a system that is usable in production in the future. Although the topic of sustainability is hot at the moment, research has yet to bring forth a fully functioning solution that can operate in a working environment.

This thesis introduces a new system design and contains the consumption data collected from the offices located at the University of Groningen in The Netherlands. This consumption data is used to estimate the possible annual energy saving potential of the system of when it would have actually been operational. Due to two unfinished components that were co-developed by two other groups, it was not possible to automatically influence the energy consumption with the Green Mind system.

In summary, this thesis offers the following contributions:

- Encourages numerous new research projects for bachelor and master thesis and allow the design and development of new 'homegrown' ideas.
- Provides accessibility to a live testing environment of actively used offices for the university.
- The designed system is to be used in production in the future, rather than being another prototype.
- Introduces a new system design for component based automation to achieve potential energy savings..
- Provides energy consumption data from offices located at the University of Groningen in The Netherlands.

1.4 Overview

This section presents how the remainder of the thesis is organized. Chapter 2 is about related work and introduces the theoretical framework and previous related research. Chapter 3 provides an overview of the tools and methods being used, where both the used hardware and software technologies are outlined. Chapter 4 presents the architecture of the developed system as a whole. The used solutions are explained, while referring to the goals set in this introduction, and their results are discussed. Chapter 5 discusses the potential results and contains the collected energy consumption measurements. The estimated results are compared to results of previous research and an explanation is given for why the measurements are as they are in Chapter 5 as well. Finally, Chapter 6 concludes this thesis with a recap of the research goals and a summary of the objectives and results, followed by future work in Chapter 7.

Chapter 2

Related work

Numerous researches have analyzed and shown the energy saving potential in office buildings. Lighting has been pointed out by various sources [10, 11, 12, 13] as an area with significant energy improvement potentials. Besides lighting office equipment (e.g., computer and monitor) influences the energy usage to a great extend. Kawamoto et al. [8 Table 4] and Webber et al. [9 Table 3] show that a large percentage of computers and monitors are not turned off but in standby mode during non-office hours (40% in Japan and 75% in US). According to the authors of [8], computers and monitors in offices are found to be in standby mode for no less than 21 hours a day. HVAC systems can also contribute to the possible energy and cost savings according to several studies [14, 15, 16]. This thesis focuses only on lighting and office equipment for energy saving potential as the HVAC installed at the Bernoulliborg building is only manageable on a per-wing basis, rather than on the envisioned per-room basis.

BMS systems are widely used in buildings to observe and grasp the status of energy consumption in operation. Besides monitoring BMS systems are able to control the internal environment of the building and can, if configured properly, reduce the energy consumption. However, these BMS systems typically do not have fine grained access to each room, or even each floor, and encompass a larger area. For example, the BMS used at the Bernoulliborg building only has access to a whole wing and cannot monitor individual rooms. Studies [17, 18, 19, 20, 21] have been presented by the scientific community to incorporate more intelligence in the BMS systems to optimize the building's energy usage. Two studies [17, 21] show a similar effort to reduce the energy consumption by equipping the building with multiple sensors and provide that information to the BMS system. Rules are created, based on the context information provided by the sensors, to achieve an optimal energy efficiency and comfort condition of the building. Although both studies seem to be one of the most well-described and complete approaches that are similar to the work in this thesis, both require a BMS. The approach in this thesis does not depend on a BMS system and can therefore be used in any building. In addition, the study presented by Han et al. [21] does not provide any information about potential energy savings that can be achieved through the system. The study by Doukas et al. [17] only provides information about the potential cumulative energy savings made through the system, rather than the potential energy savings per device (e.g., computers, lighting).

Despite the scientific interest in improving the energy consumption through BMS systems, Nguyen et al. [24] describe in a survey about energy intelligent systems that the three main energy consuming subsystems in buildings (i.e., HVAC, lighting and office equipment) also draw the attention of numerous studies. From the researched studies, some focus on one subsystem only, while others try to save energy for two or even three subsystems. The majority (22 out of 32) of the reviewed studies focus only on one subsystem, whereas this thesis focuses on two subsystems. Six studies focus on HVAC and lighting, three focus on HVAC, lighting and power plugs, and two others focus on lighting and power plugs only. iSpace [25] and Intelligent Buildings by Davidson et al. [26] are the two projects that only focus on lighting and power plugs, similar to the focus of this thesis. The work presented in [25] differs with this thesis because, although it can be used for energy savings, it is focused on autonomous environments and on student bedrooms, rather than offices. In addition, the energy consumption is not monitored. Although Davidson et al. do the same conceptually [26], the system in this thesis uses a different implementation. For example, [26] uses a Multi-Agent System (i.e., each agent is linked to, and manages, a particular entity in the building such as an office, device, or person) and relies on a Bluetooth-based indoor positioning system that requires software to be installed on the mobile phone of each user. From the three studies that focus on all three subsystems, two of these studies [27, 28] solely focus on houses instead of our focus on offices. The other study, namely the GreenerBuildings project [23], considers multiple buildings, such as offices, universities and hotels, for deployment. The architectural model of the

GreenerBuildings project was used as a starting point for the architectural model for the work in this thesis. Unlike GreenerBuildings, this thesis solely focuses on offices, does not interact with the Smart Grid and is deployed in actively used offices instead of a lab building [23].

There is one study in particular that precedes the work in this thesis. Georgievski et al. [22] proposed a system to monitor and control the office environment while coupling it with the Smart Grid. The work in this thesis differs in the fact that it does not connect with the Smart Grid and is destined to be used for a whole building in production, rather than an isolated test site of three offices.

Chapter 3

Technical approach

In this chapter the hardware and software technologies of the system are outlined. This chapter starts with a design overview of the system in Section 3.1, followed by an approach for the sensors and actuators of the system in Section 3.2. Finally, an approach for the database is given in Section 3.3, followed by the message broker in Section 3.4.

3.1 Design overview

The Green Mind system has been built out of loosely coupled components that each have their own designated tasks. This section briefly describes each component that is depicted in Figure 3.1. The components communicate with each other asynchronously through the Kafka message queue. In Chapter 4, these components will be explained in more detail. The architecture of the system is briefly addressed by this section in order of the layers (bottom-up) that are shown in Figure 3.1.

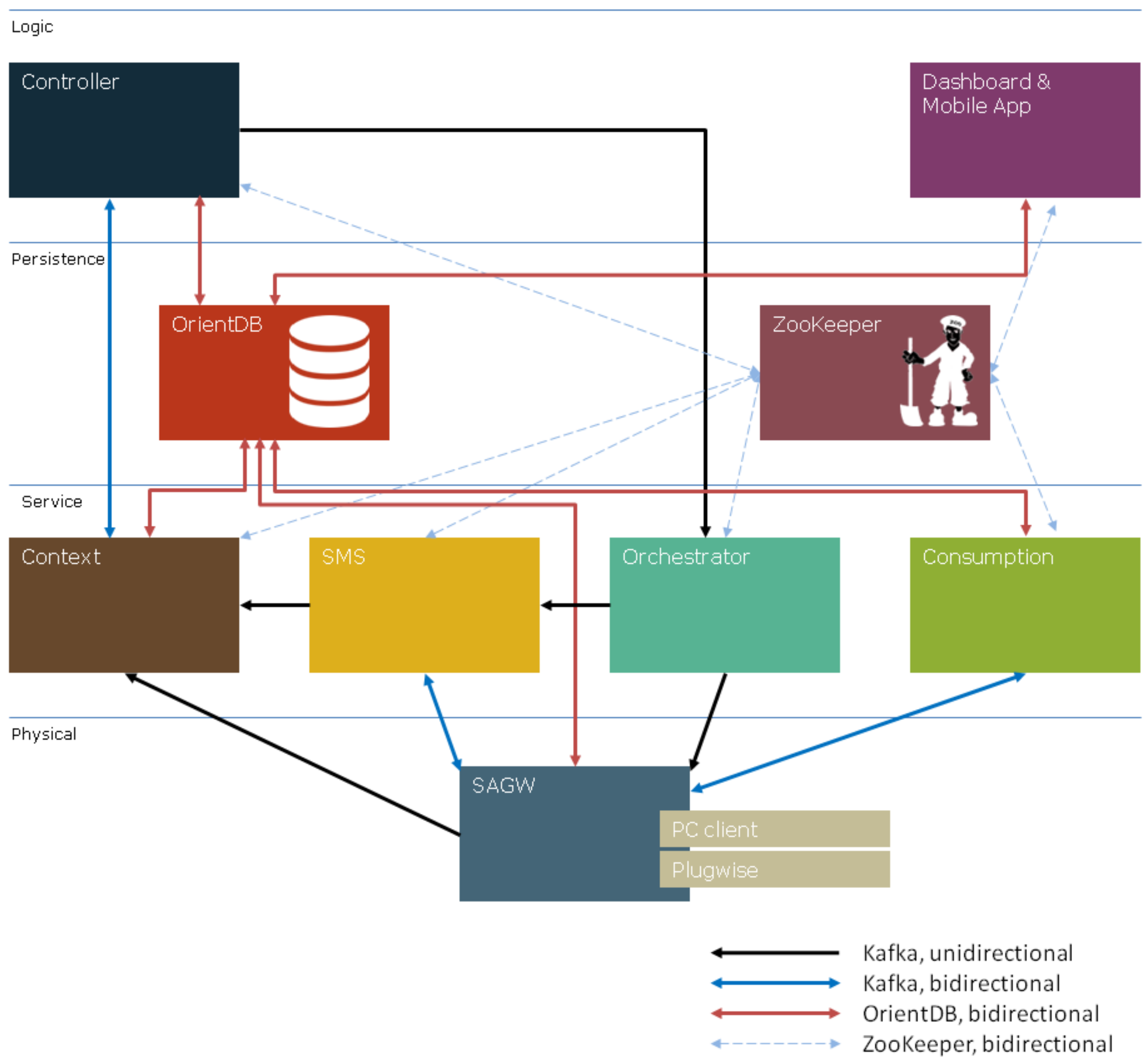


Figure 3.1: Architectural overview of the Green Mind system.

The typical operation cycle is as follows: the SAGW and SMS send messages to the context based on the changed values from their sensors and actuators; the context processes these messages to create new variables and sends the variables to the controller; the controller looks up the rules and executes them based on the received variables; messages that require action taken are then sent from the controller to actuator; the orchestrator then sends commands to either the SMS or SAGW, depending on the received message; the SMS or SAGW then executes the requested action (e.g., turn off the Plugwise device); the cycle repeats. The components do not wait until a full cycle is completed (e.g., a change in the sensor value can occur at any moment).

3.1.1 Physical layer

All the different kinds of sensors and actuators are located in the physical layer. A sensor measures a quantity (e.g., light, movement) that can be read by an external component, whereas an actuator performs actions based on commands from an external component (e.g., turn on the power, put a computer to hibernate). These sensors and actuators can be accessed through the sensor and actuator gateway (SAGW), which provides custom interfaces to all the sensors and actuators so that the system can easily access the functionality of the actuators and sensors, no matter the vendor or version of the hardware. Components in the physical layer only gather information from the sensors and actuators and merely allow the higher layers to easily access the sensors and actuators. The SAGW has currently only support for two sensors and actuators, namely the PC client and the Plugwise interface. Other sensors and actuators can be added when needed. The PC client is responsible for detecting activity on the computer and changing the state of the computer (i.e., *on*, *off*, *hibernate* or *sleep*). The Plugwise interface is responsible for easy access to the Plugwise devices that can request the energy consumption and also change the state of the Plugwise devices (i.e., *on*, *off*).

3.1.2 Service layer

Components in the service layer use the functionality of the physical layer to provide added value for the higher layers. The service components provide functionality that exceeds the 'get and set' level of the physical layer and simplifies sensor and actuator access even further. Some components create new output themselves (e.g., when processing and converting the consumption data from the Plugwise devices), while others just process high level commands and translate those to commands that can be used by the SAGW. For example, the context component creates new variables (e.g., room occupancy) by combining information received from multiple sources, such as the sleep management server (SMS) and the SAGW. The SMS enables (through the SAGW PC client) the orchestrator to manage the state of the connected computers, and provides information about activity on the computers to the context component. The orchestrator is also able to change the state of the Plugwise devices through the SAGW Plugwise interface. The consumption component uses the SAGW Plugwise interface also, namely to measure the energy consumption of the devices that are connected to the Plugwise devices.

3.1.3 Persistence layer

The persistence layer acts as a system wide long term storage. The data is stored by the components in such a way that it can easily be accessed in the future. The storage can also be used by components to store their state in, so that a component can always continue from the previous state if necessary (e.g., in the case of a hardware failure). The main data stored in OrientDB is the energy consumption measured by the consumption component, the variables created by the context, the rules from the controller, the user information from the dashboard, and the state of the connected Plugwise devices from the SAGW. Each component also registers itself to the ZooKeeper instance, so components can find each other if needed and also determine if all components are online.

3.1.4 Logic layer

The components belonging to the logic level are the high level components. These components use all the available data and functionality from the lower layers in order to make calculated decisions about the state of devices. This is also the layer where the system management components are located. The controller is the component responsible for providing the system with the ability to automate the sensor and actuator behavior, which can possibly influence the energy consumption. The main function of the dashboard and mobile app is to raise awareness of the energy consumption to the employees.

3.2 Sensors and actuators

The sensors and actuators are necessary to provide energy consumption tracking and to potentially reduce the energy consumption. These sensors and actuators need to create enough energy savings in order to justify their costs.

3.2.1 Inventory

An inventory of sensors and actuators that are feasible (technically, monetarily and privacy wise) to integrate into the system are described in this subsection. Each sensor and actuator has advantages and disadvantages that will be used as the input for the eventual approach.

Seat pressure sensor

A seat pressure sensor can be placed at a location where it can detect the pressure of an occupant sitting on the seat. This can either be inside, below or on top of the seat. As soon as an occupant sits on the seat, the seat pressure sensor detects the weight and signals it to the receiving party.

Advantages

- Detect room occupancy, unless the seat is moved to another room.

Disadvantages

- Does not detect computer usage (e.g., moving the seat to another desk for a meeting).
- Not all seats are suitable for placing a seat pressure sensor (e.g., wooden seats).
- Requires significant effort and costs to install and integrate in existing environment.

Price: 65-235€ (custom built excluding development and build costs [29, 30, 31] or prefabricated [32, 33]).

Energy consumption sensor

An energy consumption sensor can detect the energy consumption of connected appliances (e.g., computer or lights). The sensor can be placed between the appliance plug and the socket for easy installation. The sensors can also be equipped with the ability to wirelessly switch on or off appliances, making the sensors not only useful to actively monitor but also to influence the energy consumption.

Advantages

- Insight in the energy consumption of connected appliances.
- Switch appliances on or off (e.g., after working hours).
- Easy installation.

- Wirelessly switch on or off appliances.
- A power strip provides an easy and cheap way to increase the number of connected appliances (e.g., for connecting multiple lights).

Disadvantages
- Protrudes from the socket (in case the sensor is not integrated into the wall socket).
- Easy for users to avoid (i.e., by using another socket or by removing the energy consumption sensor).

Price: 35-65€ [6, 7].

PIR sensor
A passive infrared (PIR) sensor can be placed at a location where it can detect movement. PIR sensors only detect movement, rather than the location of that movement. As the range and field of view of a PIR sensor is limited, it is often placed at the ceiling in order to maximize coverage. As soon as a PIR sensor detects movement it signals it to the receiving party.

Advantages
- Detect room occupancy.
- Easy installation.
- Unobtrusive placement.
- Available as multi sensor (light intensity and PIR).

Disadvantages
- Reliability varies (e.g., by direct sunlight or direct wind from an air conditioner or heater)
- Does not detect the location of movement.
- Requires constant movement.
- Does not detect very slow movement.

Price: 60-250€ (custom built excluding development and build costs [29, 30, 38] or prefabricated [36, 37]).

Light sensor
A light sensor can detect light intensity in low light conditions (indoor), high light conditions (outdoor) or both. As the light intensity measured highly depends on the location of the light sensor (e.g., near a window), placing multiple light sensors in a shared office (with different desk locations) can improve the accuracy of influencing the energy consumption based on the light intensity.

Advantages
- Determine whether lights should be switched on or off.
- Available as multi sensor (light intensity and PIR).

Disadvantages
- Minimum acceptable light intensity level depends on the user.
- Interference with lights being switched on.
- Highly dependent on location.

Price: 55-250€ (custom built excluding development and build costs [29, 30, 40] or prefabricated [36, 37, 39]).

Computer software sensor

A computer software sensor can detect input, such as mouse and keyboard, activity of the user. As soon as the mouse is moved, the scroll wheel used or a key is pressed, activity is registered by the computer software sensor. The amount of time after the last registered activity can be used to determine the idle time of the computer. However, using only the input devices to determine if a computer is idle may not be enough. For example, consider a complex program that requires several hours to complete. One way to solve this problem is by also monitoring the CPU and GPU usage of a computer. Another way is to allow a select group of users to temporarily override the activity detection mechanism. The computer software sensor can also be equipped with the ability to turn a computer off, to sleep and to hibernate.

In case of laptops, the portability aspect does not necessarily cause concerns for the computer software sensor to function. As long as the laptop remains reachable by the other components of the system, it can still be used to turn the laptop to *sleep*, *hibernate*, or *off*. The energy consumption measurements for a laptop remain a point of interest with or without the computer software sensor (e.g., laptop is charged elsewhere or is not plugged in at the office because of remaining battery life).

Advantages

- Detect computer usage.
- Easy installation at no additional hardware costs.
- Unobtrusive placement.
- Updatable to incorporate new features.

Disadvantages

- Requires constant activity.
- Easy for users to avoid (e.g., by killing the process of the software sensor).

Price: 0€ (excluding development costs).

Ultrasonic sensor

An ultrasonic sensor generates sound waves and evaluates their echos to measure the distance to an object. The sensor can be placed in front of the user (faced to the office chair). Desk usage can be detected by measuring the difference between an empty and occupied office chair.

Advantages

- Detect desk usage.
- Does not require movement.

Disadvantages

- Obtrusive placement (in front of user).
- Reliability varies (e.g., rotating the office chair).
- Does not detect computer usage (e.g., user is making notes in front of the computer).

Price: 65-75€ (custom built excluding development and build costs [29, 30, 41, 42]).

Other sensors

Several other sensors were considered but dropped for consideration for the actual approach:

- *Radio frequency identification* (RFID), *near field communication* (NFC) or *WiFi* tags, due to the accompanying requirement to use badges. Badges can be lost, forgotten, and are not ideal in an open building such as an university because of the amount of visitors and students.

- *Door sensors*, due to inability to detect multiple persons in an office and due to the inaccuracy (e.g., standing in the door opening to simply wave to a colleague).
- *Cameras*, due to privacy concerns.
- *Mobile phone tracking software*, due to privacy concerns and similar disadvantages as the previously mentioned tags.

3.2.2 Computer

The computer is the main center of activity in an office. Per computer in an office there are two variables to be measured to determine context and to influence the energy consumption:

- *Energy consumption*, where either the computer and monitor are measured, for determining context, separately or combined. A baseline measurement of the energy consumption, compared to later measurements, can measure how effective the solution is.
- *Computer usage*, which consists of the idle time (i.e., the computer is powered-on but not used) and the active time (i.e., the computer is powered-on and used). The idle and active time are both important to determine context and to influence the energy consumption.

The following sensors can be applied for the energy consumption and computer usage:

- Energy consumption sensor
  To monitor the energy consumption of the computer, monitors, or both combined.
- Ultrasonic range sensor
  To determine if someone is sitting in front of the desk.
- Computer software sensor
  To detect computer usage and to influence the power state (*sleep*, *hibernate* or *off*), which has the potential to affect the energy consumption.
- Seat pressure sensor
  To determine if someone is setting on their seat.

To measure the energy consumption of the computer, there are two possible scenarios:

1. 1x energy consumption sensor and 1x power strip. The power strip will be used to connect both computer and monitor(s) to. The energy consumption sensor will measure the total energy consumption of all devices connected to the power strip.
2. 2x energy consumption sensor and 1x (optional) power strip. The power strip will only used when a computer has multiple monitors. The energy consumption sensor will measure the energy consumption of the computer and monitors separately.

The advantage of using the second scenario is that it will be possible to turn off a monitor completely using the energy consumption sensor. With the first scenario it will only be possible to use the standby mode of the monitor (which still uses a small amount of energy), but the upside is that it will cost nearly half of the first scenario. Kawamoto et al. [8, Table 5] show that an average monitor uses 1.5W (LCD) to 5W (CRT) in standby mode, which is automatically applied by the operating system when a computer is put in S3 (commonly referred to as *standby*, *sleep* or *suspend-to-ram*), S4 (commonly referred to as *hibernate* or *suspend-to-disk*), or off. Kawamoto et al. [8, Table 3] also show that a computer and monitor have an average power-on time of 6.9 hours per day during office hours, including 3.9 hours of idling time. Studies also show [8 Table 4, 9 Table 3] that a large percentage of monitors during non-office hours are not turned off but in standby mode (40% in Japan and 75% in US). From the observed patterns in [8], a monitor could be in standby mode for 21 hours a day. With CRT monitors discontinued for years, the LCD monitor is widely used in offices. With 21 hours per day in standby mode, this results in a total of 0.0315 kWh potential waste each day. With energy prices per kWh being an estimated 0.23€ [46], each monitor costs roughly 0.0073€ each day. As the energy consumption sensors start at 35€ it would take more than 13 years to break-even, resulting in a low return on investment. To reduce complexity and due to the low return on investment of the second scenario, the decision was made to use the first scenario.

To measure computer usage and influence the energy consumption of the computer, there are two possible scenarios:

1. 1x ultrasonic range sensor, 1x seat pressure sensor and 1x computer software sensor. As single sensors, the ultrasonic range sensor and seat pressure sensor both have severe shortcomings, but reliable computer usage detection can be achieved by combining both sensors.
2. 1x computer software sensor. The computer software sensor will measure the amount of time the pc is idle.

Based on the computer usage, and particularly when the computer is not being used, the computer's power status (i.e., on, S3, S4 or off) can be changed to influence the energy consumption. In both scenarios can the computer software sensor be used to put the computer in a different power status to achieve potential energy savings, whereas the operating system will automatically put the monitor in standby mode when the power status of the computer changes. In the second scenario the computer software sensor can detect computer usage (e.g., by monitoring the input devices), even though it can also be used to improve the accuracy of the first scenario. The other two sensors of the first scenario both have their shortcomings, but combining the sensors can achieve reliable computer usage detection. The advantage of using these two sensors, especially when combined with the computer software sensor, is that computer usage can be detected almost instantly and also with better accuracy compared to the second scenario. The main shortcoming of the second scenario is that acting upon detecting when the computer is not being used cannot happen instantly. For example, when only input devices are used for computer usage detection, it is unlikely that the user is constantly using the input devices of the computer. A delay (e.g., 10 minutes) can partially solve this, although a delay will never achieve the same accurate results as using the first scenario. However, as the first scenario already costs roughly 130€ (without the required computer software sensor) and because it would still need a delay (e.g., the user is only grabbing a piece of paper from a drawer), the decision was made to use the second scenario.

3.2.3 Lighting

Lights are used throughout the whole building, not only the office lights can be influenced but also the lights in the hallways. For the lights in the building there are three variables to be measured to determine context and to influence the energy consumption:

- *Movement*, to determine context and influence the energy consumption. The movement can be used to determine whether lights should be switched on or off.
- *Energy consumption*, where the measurement, for determining context, can either be done over a single light or multiple lights at the same time. A baseline measurement of the energy consumption, compared to later measurements, can measure how effective the solution is.
- *Light intensity*, where the value can be used to determine whether lights should be switched on or off. The light intensity is important to determine context and to influence the energy consumption.

The following sensors can be applied to measure movement, energy consumption and light intensity:

- Light sensor
  To measure the light intensity (in lux) near the location of the sensor.
- Energy consumption sensor
  To monitor the energy consumption of the lights, either over a single light or multiple lights at the same time.

- PIR sensor
  To determine if a room (or hallway) is occupied or not.

To influence the energy consumption of the lights, there is three possible scenario:
1. Ax energy consumption sensor, Bx light sensor and Cx (optional) power strip, where the values of A, B and C depend on the situation of the lights.
2. Ax energy consumption sensor, Bx light sensor, Cx PIR sensor and Dx (optional) power strip, where the values of A, B, C and D depend on the situation of the lights.
3. Ax energy consumption sensor, Bx PIR sensor and Cx (optional) power strip, where the values of A, B and C depend on the situation of the lights.

The type and amount of sensors required per location depend on the situation. For a busy hallway one light sensor and one energy consumption sensor, with a power strip to connects all lights, can suffice to maximize potential energy savings. On another hand, a hallway that is not often used can use a PIR sensor instead of a light sensor. In case the situation requires a light sensor, the energy consumption sensor can be used to switch off the lights when the intensity measured is greater than a predefined value. The measured intensity from the light sensor can also be used to switch on the lights using the energy consumption sensor when the value is below the predefined value. On the other hand, the PIR sensor can be used for locations such as rooms and hallways, where lights should be switched on when movement is detected. As PIR sensors only detect constant movement, a delay is often required to have the lights not constantly switch between on and off. Multiple possibilities of switching lights on or off are achievable in case both a light sensor and PIR sensor, combined with an energy consumption sensor, are used. To maximize the potential energy savings in this case, it is recommended to let the PIR sensor have priority over the light sensor when the light intensity is under a predefined value, and to let the light sensor have priority over the PIR sensor when the light intensity is above a predefined value. In general, the key elements to decide the sensors for a location are the amount of users that pass through the area, the amount of daylight entering the area, the type of area, and the personal preferences of the users. This resulted in the decision to have the ability to use all three possible scenarios.

3.2.4 Other

There are other devices (e.g., a beamer, a warm water boiler and an oven/microwave) that are not available in high quantities but that are still very common in office environments and used very regularly throughout the day. These devices can be turned off outside office hours to save power. For these devices there is at least one variable to be measured to determine the context:
- *Energy consumption*, where the measurement, for determining context, can be done over each device. A baseline measurement of the energy consumption, compared to later measurements, can measure how effective the solution is.
- *Variable X*, where X can be used to influence the energy consumption of a device. The only requirement for the variable is that a sensor is required for the measurements.

The following sensors can be applied to measure movement, energy consumption and light intensity:
- Energy consumption sensor
  To monitor the energy consumption of the device.
- Sensor X
  To measure variable X.

Even though these devices are not placed in the computer and lighting category, it is always possible to include other variables (e.g., *movement*) or sensors (e.g., *PIR sensor)* that can be used to influence the energy consumption. Scenarios of using sensors other than the energy consumption sensor depend on the type of device. Most devices are only used during office hours and can be switched off safely otherwise, whereas other devices can maximize their potential energy savings by using additional sensors (e.g., using a PIR sensor to only enable the stereo system when movement is detected). In all possible scenarios is an energy consumption sensor required to determine how effective the solution is.

3.3 Databases

The database is necessary to store and retrieve the data (e.g., the sensor measurements) for the components of the system. The data can be stored in traditional - *relational* - databases using tables. The primary difference is that in a graph database the relationships are stored at an individual record level, whereas in a relational database the structure is defined at a higher level (i.e., the table definitions). One of the main advantages is that graph databases provides index-free adjacency (i.e., graph traversals can be performed with no index lookups) that can lead to a much better performance. Each sensor measurement contains relationships to other data such as the floor, building, time and date, and room or user. As a large amount (i.e., 1,000,000) of sensor measurements with a traditional database caused severe performance issues (e.g., retrieve the total energy consumption for a certain hour on a specific date), the decision was made to use a graph database instead of a traditional database. This also enables the ability to use advanced queries on the stored information, for which query languages such as SPARQL [47] and Cypher [53] have been developed.

3.3.1 Inventory

An inventory of databases are described in this subsection. Each database has advantages and disadvantages that will be used as the input for the eventual approach. The most described graph database choices are [76, 91, 92, 93]:

- Neo4j [117].
- Titan [118].
- HyperGraphDB [119].
- AllegroGraph [120].
- DEX [121].
- InfiniteGraph [122].
- OrientDB [123].

The following graph databases were dropped for consideration after an initial review:

- *Titan* due to the large number of issue reports [94], (third party) licensing problems [113], and an unpredictable fluctuating performance [114].
- *HyperGraphDB* due to an inadequate community [49], no replication mechanisms [96], and the time between subsequent releases being nearly 2 years [97, 98].
- *AllegroGraph* due to only supporting 5 million nodes in the free version [99], an inadequate community [101], support that is accessible only through email (e.g., no forums) [100], and a focus on describing and interchanging metadata on the web (i.e., Resource Description Framework (RDF) information) rather than a general purpose database [102].
- *InfiniteGraph* due to the pay as you go pricing starting at 4.000 EUR (the price depends on the number of supported nodes and edges) [103], an inadequate community [104], and no replication mechanisms [105].

The three remaining graph databases are subject to a closer review - Neo4j is described in Subsection 3.3.2, OrientDB in Subsection 3.3.3, and DEX in Subsection 3.3.4.

3.3.2 Neo4j

Neo4j is a robust and fully ACID transactional Java persistence engine that stores data structured in graphs. It is an open-source database that is supported and developed by Neo Technology [48].

There are three different versions of Neo4j, released for different purposes [49]:

- Community edition (GPL license). Only community support and is allowed only for open source projects. Price: 0 EUR per year.
- Advanced edition (commercial or AGPL license) - includes *Advanced Monitoring*. This edition comes with professional email support that is available 10 hours a day, 5 days a week. Both open source projects and commercial projects are allowed. Price: 0 EUR per year for open source or 6.000 EUR per year for commercial projects.
- Enterprise edition (commercial or AGPL license) - includes *High Availability Clustering, Online Backups* and *Advanced Monitoring*. This edition comes with professional email support that is available 24 hours a day and 7 days a week. Both open source and commercial projects are allowed. Price: 0 EUR per year for open source or 24.000 EUR per year for commercial projects.

Advantages

- Support for many languages and frameworks [50].
- Active community for deployment, development and problems [51].
- Used in production by large corporations such as Adobe, Mozilla, Lufthansa and Cisco [52].
- Excellent availability and horizontal (read) scaling characteristics for up to dozens of servers [54].
- Active development. A new major version comes out approximately every six months, with minor versions (containing mostly bug fixes) every month [59].
- Great documentation available, such as guides, tutorials, videos and books [60].
- Improvements to vertical scalability are scheduled for 2013 [55].

Disadvantages

- High performance relies heavily on the available RAM of the system [56].
- The high availability clustering features (used for availability and horizontal scalability) require the enterprise edition [57].
- Write scalability is limited. Clients can write to slave nodes but the master node remains the limited factor [58].

3.3.3 OrientDB

OrientDB is an open source database with features from both document and graph database systems. It is developed and supported by Orient Technologies and two of the three versions can be used free of charge for both commercial and free usage. Professional support plans are available for 2.500 to 4.000 EUR, depending on the license and length [64].

There are three different versions of OrientDB released [49, 50]:

- Standard edition (Apache2 license). Support is limited to the community, but professional support plans are available. Price: 0 EUR per year.
- Graph edition (Apache2 license) - includes *TinkerPop Stack* [65]. Support is limited to the community, but professional support plans are available. Price: 0 EUR per year.
- Enterprise edition (commercial license) - includes *TinkerPop Stack*, *Query Profiler, Configurable Alerts* and *Production Support* for 1 year. This edition comes with professional email support that is available 9 hours a day, 7 days a week. Price: 4.000 EUR per year.

Advantages
- Supports both document and graph data models [68].
- Uses query language similar to SQL [61].
- Support for many languages and frameworks [112].
- Distributed architecture: horizontal scalability (read and write) to improve performance and availability [106, 107].
- Replication can be configured to use either synchronous mode (always consistent) or asynchronous mode (eventual consistency) [106].
- Supports multi-master replication, allowing each node to read and write to the database [106].
- Great documentation available, such as guides, tutorials, videos and books [107].
- Improvements to vertical scalability (e.g., distributed transactions) are scheduled for version 2.0 which is expected to be released before the end of 2013 [79].
- Active development, a new major version comes out approximately every six months, with minor versions (containing mostly bug fixes) every month [110, 111].

Disadvantages
- Not used in production by large corporations (only in medium sized corporations) [67].
- Scalability/replication is limited to local networks only [69, 73, 78].
- Community is not as large and active as Neo4j, but questions are usually answered within a day or two [73].

3.3.4 DEX
DEX is a high-performance and scalable graph database system. It is developed, supported and licensed under a proprietary license by Sparsity Technologies.

There are three different configurations for the DEX licenses available [80]:
- Size - small (up to 1 million objects), medium (up to 100 million objects), large (up to 1 billion objects) and very large (more than 1 billion objects). Licenses can be upgraded to a higher size.
- Sessions - the number of concurrent sessions, between 1 and unlimited.
- High availability - provides horizontal scalability that allows DEX to handle larger workloads.

There are five different licenses of DEX available that have the same amount of features, depending on the selected configurations [80]:
- Evaluation license - for personal testing purposes. The configurable size is limited to small only.
- Research license - for academic research purposes. All configurations are available, but registration is required.
- Development license - for business testing purposes. All configurations are available, but registration is required.
- Commercial license - for business production purposes. All configurations are available. Price: 475 EUR per year for the most basic configuration to 11.515 EUR per year for the most complete configuration. Support hours are based on the configurable size and professional support is available 8 hours a day, 5 days a week [81].

Advantages
- Great documentation available, such as guides, tutorials and examples [109].
- Development is widely focused on multiple aspects of the database [85].
- Efficient usage of available disk and memory resources [83].
- Active development, a new major version comes out approximately every six months [112].

Disadvantages

- Does not support many languages and frameworks [66].
- Inadequate community, the number of new posts per week on the community forums are limited but questions are usually answered within a week [87].
- Expensive compared to Neo4j and OrientDB.
- A failure of the master node leaves the system non-operational, despite a master-slave implementation [89].
- Not used in production by large corporations, the available scenarios only describe research projects with limited periods [88].
- There are no minor version releases [112].

3.3.5 Overview

The following guarantees must be provided by the graph database:

- *Scalability*. It is likely that one database will be used per building, university or company. With the amount of sensor measurements done it is important for a database to handle increased load in such a way that the throughput can increase when resources (e.g., more servers) are added.
- *Availability*. As the components of the system depend on the data that is stored in the database it is important that the database is always accessible. Without the data important decisions cannot be taken to influence the energy consumption and is it possible that sensor measurements from a specific time are lost.
- *Performance*. If the database is unable to cope with a large amount of new sensor measurements (i.e., the inserts are coming in at a higher rate than the database can process), it will eventually come to a stop. The read performance is also important as the components of the system rely on the sensor measurements. The performance of reads and writes simultaneously is important too to ensure that all system components continue to function.
- *Documentation*. The documentation of the database can address topics like tutorials, how to setup the database, drivers, language bindings, and tutorials. A database is not considered without well written and complete documentation as there are too many uncertainties and risks involved.
- *Community*. An important aspect of a database is the community evolving around it. Without a community it is often hard for users to ask questions and find tutorials about the product. A community is also important to ensure that development continues with input from the users (e.g., suggest new features or submit bug reports).
- *Price*. A free or open-source database is preferred because of the open character of the system. This includes not limiting the amount of possible nodes for the database.
- *Usage*. The usage, or adoption rate, is an important aspect of a graph database. It affects aspects such as development (e.g., continue with input from the users or the possibility to add patches or functionality in open-source software), stability (e.g., it is unlikely a company is going to use unstable software in production) and support (e.g., more users available to ask and answer questions).

For each of the seven guarantees there is one graph database to provide the 1st best solution, with the other two graph databases providing the 2nd or 3rd best solution. The guarantees are compared based on the closer review from subsections 3.3.2, 3.3.3, and 3.3.4 and are shown in Table 3.1. A '++' denotes an exceptional property, a '+' denotes a positive property, whereas a '-' denotes a negative property for a specific graph database.

	DEX	OrientDB	Neo4j
Scalability	1st + Read and write. + Internet network support.	2nd + Read and write. - Only local network support.	3rd - Read. + Internet network support.
Availability	3rd + Master-slave replication. - Master failure leaves system non-operational.	1st ++ Multi-master replication.	2nd + Master-slave replication. - High availability requires the enterprise edition.
Performance	2nd - Similar performance as Neo4j [75, 76, 77, 82] but severely lower than OrientDB.	1st + Best performance [75, 76, 77, 115].	2nd - Similar performance as DEX [75, 76, 77, 82] but severely lower than OrientDB.
Documentatio n	2nd + Great documentation available.	2nd + Great documentation available.	1st ++ Best documentation available.
Community	3rd - Smallest (but active) community.	2nd + Substantial and active community.	1st ++ Largest and most active community.
Price	3rd - Always requires a license unless it is only for testing or research purposes. - High availability requires a separate configuration.	1st + Nearly all features are available for free. + The enterprise edition is the cheapest compared to DEX and Neo4j.	2nd - Enterprise edition is the most expensive (only for commercial projects). - High availability requires the enterprise edition.
Usage	3rd - Only research projects.	2nd + Used by medium sized companies.	1st ++ Used by large sized companies.

Table 3.1 - *Overview between Neo4j, DEX and OrientDB about scalability, availability, performance, documentation, community, price and usage.*

3.3.5 Conclusion

As shown in Table 3.1, the DEX graph database only provides the best solution for scalability. Even though scalability is absolutely important for the components of the system, OrientDB provides almost similar scalability features with the only scalability limitation being no internet network support. As the DEX graph database provides the 2nd or 3rd best solution for all the other guarantees, it is not considered anymore for the final approach.

The remaining two graph databases, Neo4j and OrientDB, both have best solutions for different guarantees. OrientDB excels in scalability, availability, performance and price, whereas Neo4j excels in documentation and community. However, Table 3.1 also shows that the guarantees of Neo4j and OrientDB are intertwined with respect to each other. Even though all guarantees are important, some are more important than others and also, the guarantees of two graph databases can both be satisfactory for the final approach. In case of the scalability of the database, OrientDB clearly wins as it supports both read and write scalability. The availability of both OrientDB and Neo4j are satisfactory, even though Neo4j only supports high availability in the enterprise edition. In terms of performance is OrientDB a clear winner, while Neo4j has the largest community, largest usage and by far the best documentation in terms of quantity, quality and diversity. On the other hand, Neo4j also has the most expensive enterprise edition and is missing important functionality for scalability in the free version. The fact that the performance and scalability of OrientDB are better and that the documentation, usage and community of OrientDB are also sufficient led to the decision to use OrientDB instead of Neo4j for the final approach.

3.4 Message queue

The message queue can be used by the components of the system to communicate with each other, with or without knowing the physical location of the other components. Message queues can significantly simplify the implementation of the separate components and also improve performance, scalability and reliability. Another advantage of using a message queue is that the sender and receiver do not need to communicate with the message queue at the same time as the messages are stored onto the queue until the recipient receives the message. As a result, the communication between different components is asynchronous. The communication between the components is further discussed in Section 4.4, whereas the communication directions between the different components are depicted in Figure 3.1. Because of the aforementioned advantages the decision was made to use message queues for the communication of the system.

3.4.1 Inventory

An inventory of message queues are described in this subsection. Each message queue has advantages and disadvantages that will be used as the input for the eventual approach. The most described message queue choices are [132, 133, 134, 135, 136]:

- ActiveMQ [124].
- Zer0MQ [125].
- Kafka [126].
- RabbitMQ [127].
- Qpid [128].
- Amazon SQS [129].
- HornetQ [130].
- Apollo [131].

The following message brokers were dropped for consideration after an initial review:

- *Zer0MQ* due to having no guaranteed delivery of messages [137] and that most functionality requires you to implement and combine various components of Zer0MQ [138].
- *Apollo* due to an inadequate documentation [131] and community [149, 150].
- *Amazon SQS* due to being software as a service (SaaS) only [139] and having a pay-as-you-go pricing scheme [140].
- *Qpid* due to number of bug reports [141] and having an inadequate community [142, 143].
- *ActiveMQ* due to the number of user complaints [145, 146, 147] and having a low performance [135, 136, 144].

The three remaining message queues are subject to a closer review - RabbitMQ is described in Subsection 3.4.2, Kafka in Subsection 3.4.3, and HornetQ in Subsection 3.4.4.

3.4.2 RabbitMQ

RabbitMQ is an open source enterprise messaging queue based on the emerging AMQP [183] standard. RabbitMQ is developed and supported by GoPivotal Inc., whereas VMWare provides a commercial licensed release of RabbitMQ under the vFabric™ brand name [151]. Professional support plans are available by both GoPivotal Inc. and VMWare for undisclosed prices.

Advantages

- Largest community compared to Kafka (3rd) and HornetQ (2nd) [167, 168, 169, 170, 171, 172].
- Professional support available by two companies.
- Well written and complete documentation [173, 174].
- Used by large companies such as VMWare [176], Nokia [176], Huffington Post [176], Aadhaar [176], Digg [178] and NASA [178].
- Replication support for a cluster [180].
- Uses master-slave for high availability/scalability [156].

Disadvantages

- The amount of configuration required for high availability/scalability [156].
- Clients can only write to the master node [132, 156, 182].

3.4.3 Kafka

Kafka is an open source high-throughput publish-subscribe messaging queue that is scalable, durable and fault-tolerant by design. Kafka was originally developed at LinkedIn [152] before it became an Apache project. LinkedIn is still involved in the development of Kafka and uses Kafka internally for several processes [153].

Advantages

- High availability/scalability is built in and easy to setup [157].
- The client maintains what was received and can request previous messages (e.g., at startup) if needed [159].
- The setup and code required is the easiest compared to RabbitMQ (2nd) and HornetQ (3rd) [163, 164, 165].
- Well written and complete documentation [161, 162].
- Used by large companies such as LinkedIn, Twitter, Tumblr, Foursquare, Netflix and Mozilla [166].
- Best performance compared to RabbitMQ (2nd) and HornetQ (3rd) [135, 136, 143, 144, 175].
- Uses a variant of master-slave for high availability/scalability [153, 159].
- Clients can write to each node [159].
- Replication support for a cluster [159].

Disadvantages

- Smallest community compared to RabbitMQ (1st) and HornetQ (2nd) [167, 168, 169, 170, 171, 172].
- Requires external application (i.e., Zookeeper) for discovering message topics and nodes [159].
- No professional support available.

3.4.4 HornetQ

HornetQ is an open source multi-protocol and asynchronous messaging system designed with usability in mind. HornetQ was originally developed as JBoss Messaging 2.0 and is currently developed by the community with assistance from a small team located at Red Hat/JBoss [154]. Red Hat/JBoss also provides professional support for HornetQ through their regular subscription model [155].

Advantages

- Professional support available by two companies [155].
- Replication support for a cluster [181].
- Clients can write to each node [181].
- Uses a variant of master-slave for high availability/scalability [181].
- Larger community compared to Kafka (3rd) [167, 168, 169, 170, 171, 172].

Disadvantages

- The amount of configuration required for high availability/scalability [158].
- Large, but unreadable and complex documentation (e.g., often no explanations, lack of structured online examples) [160].
- Lowest performance compared to Kafka (1st) and RabbitMQ (2nd) [135, 136, 143, 144, 175].
- Not used by large companies except for Last.fm [179].
- Requires shared storage for scalability that is accessible by all nodes [181].

3.4.5 Overview

The following guarantees must be provided by the message queue:

- *Scalability*. It is likely that one message queue will be used per building, university or company. With the amount of messages sent (e.g., sensor measurements) it is important for a message queue to handle increased load in such a way that the throughput can increase when resources (e.g., more servers) are added.
- *Availability*. As the components of the system depend on the data that is sent through the message queue it is important that the message queue is always accessible. Without the data important decisions cannot be taken to influence the energy consumption.
- *Performance*. If the message queue is unable to cope with a large amount of data sent through the message queue (i.e., the data is coming in at a higher rate than the message queue can process), it will eventually come to a stop.
- *Documentation*. The documentation of the message queue can address topics like tutorials, how to setup the message queue, and tutorials. A message queue is not considered without well written and complete documentation as there are too many uncertainties and risks involved.
- *Community*. An important aspect of a message queue is the community evolving around it. Without a community it is often hard for users to ask questions and find tutorials about the product. A community is also important to ensure that development continues with input from the users (e.g., suggest new features or submit bug reports).
- *Usage*. The usage, or adoption rate, is an important aspect of a message queue. It affects aspects such as development (e.g., continue with input from the users or the possibility to add patches or functionality in open-source software), stability (e.g., it is unlikely a company is going to use unstable software in production) and support (e.g., more users available to ask and answer questions).

For each of the six guarantees there is one message queue to provide the 1st best solution, with the other two message queues providing the 2nd or 3rd best solution. The guarantees are compared based on the closer review from subsections 3.4.2, 3.4.3, and 3.4.4 and are shown in Table 3.2. The scalability and availability guarantees are grouped together in Table 3.2 because of their related properties. A '++' denotes an exceptional property, a '+' denotes a positive property, whereas a '-' denotes a negative property for a specific message queue. Regarding the scalability and performance guarantees for the Green Mind system, there are no specifics about the actual requirement for these guarantees due to several reasons. The main reasons are that the amount of messages highly depend on the number of sensors and actuators (currently undecided), how often the measured quantities change from the sensors, and the deployed scale of the system.

Regardless, the scalability and the performance are an important aspect of the system, especially when it is likely that one message queue instance will be used per building, or even for a whole university.

	RabbitMQ	Kafka	HornetQ
Scalability and Availability	2nd + Can send to master. - Amount of configuration.	1st ++ Can send to each node. + Amount of configuration.	2nd ++ Can send to each node. - Requires shared storage. - Amount of configuration.
Performance	2nd + Second best performance compared to Kafka and HornetQ.	1st ++ Best performance compared to RabbitMQ and HornetQ.	3rd - Worst performance compared to RabbitMQ and Kafka.
Documentation	1st ++ Best documentation available.	2nd + Great documentation available.	3rd - Worst documentation available.
Community	1st ++ Largest and most active community.	3rd - Smallest (but active) community.	2nd + Substantial and active community.
Usage	1st + Used by large sized companies.	1st + Used by large sized companies.	2nd - Used by almost no (large) companies.

Table 3.2 - *Overview between RabbitMQ, Kafka and HornetQ about scalability and availability, performance, documentation, community and usage.*

3.4.6 Conclusion

HornetQ never provides the best solution for any of the six guarantees, as shown in Table 3.2. While providing the second best solution for usage, community, scalability and availability, it also provides the worst solution for performance and documentation. As RabbitMQ and Kafka both provide better or equal solutions for all six guarantees, the decision was made to not consider HornetQ anymore for the final approach.

The remaining two memory queues, RabbitMQ and Kafka, provide an equal amount of best solutions. RabbitMQ provides the best solution for documentation, community and (shared) usage, whereas Kafka provides the best solution for scalability and availability, performance and (shared) usage. However, not all guarantees have the same importance and there are also guarantees that are satisfactory for the final approach for both remaining memory queues. The documentation of RabbitMQ is better and the community larger, but the documentation and community of Kafka are satisfactory too. In terms of the performance, scalability and availability is Kafka the clear winner. The fact the scalability and availability of Kafka are better than that of RabbitMQ and that the performance of Kafka is at least two times that of RabbitMQ [175] led to the decision to use Kafka instead of RabbitMQ for the final approach.

Chapter 4

Implementation

Chapter 4 describes the office environment and the architecture of the Green Mind system that was installed to monitor and influence the energy consumption.

First, in Section 4.1, the layout of the offices is introduced in order to give a better understanding of the operating environment and the scale. Then an overview is given of the complete architecture in Section 4.2 before discussing the individual components in detail in Section 4.3. Finally, Section 4.4 handles the communication between the components and how the components find each other.

4.1 Office environment

The main area to be controlled is located on the top fifth floor of the Bernoulliborg building and consists of two adjacent corridors that connect in a right angle at the north-east corner of the building ( ). In total twelve areas are controlled by the system, located on the fifth floor and connected to each other through the two included hallways. The areas that are controlled by the system are as follows:

- 8x office.
- 2x hallway.
- 1x kitchen area.
- 1x meeting area.

The first eight offices pertain to employees from the Distributed Systems group at the university. After the system is tested and found stable, more offices from the university are going to be connected the Green Mind system.

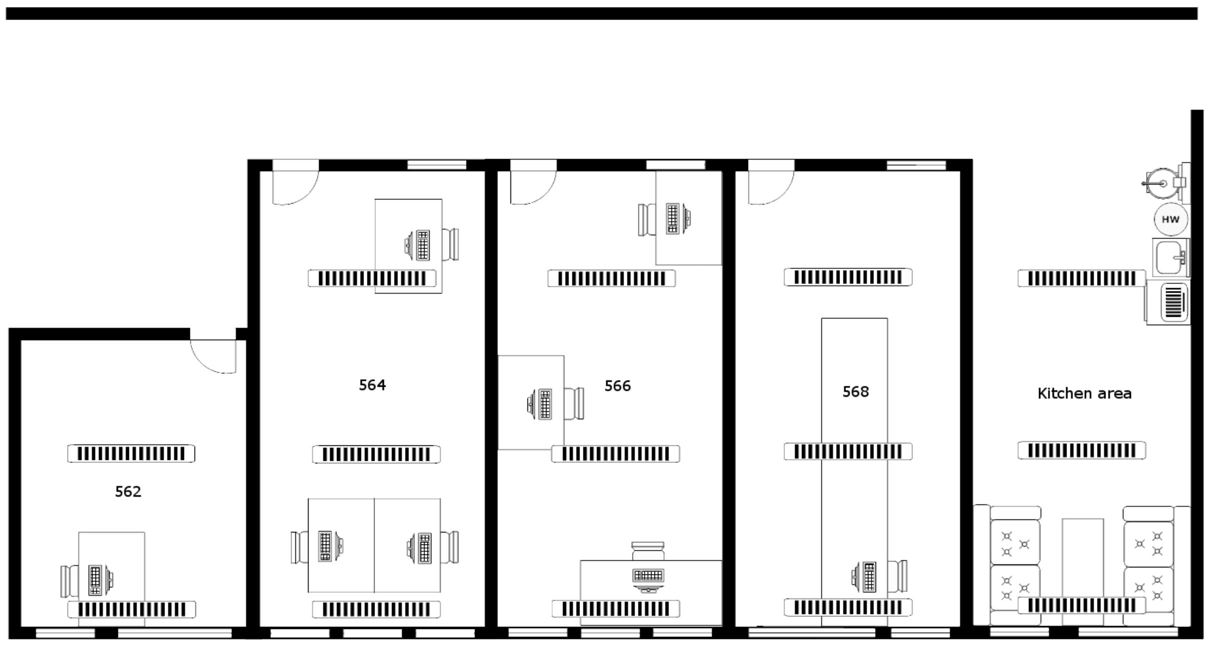


Figure 4.1: Map of the offices and kitchen area on the east side of the fifth floor.

The east side of the fifth floor consists out of four offices and a kitchen area. The offices give room to one or more employees. Figure 4.1 shows the layout of the workplaces and light fixtures in those offices as well as the kitchen area.

Figure 4.2 shows the layout of the north wing, which contains the other half of the environment controlled by the system. The right side of the hallway in Figure 4.1 connects to the bottom of the hallway in Figure 4.2. The layout of the workplaces and light fixtures in the north wing is depicted in Figure 4.2. The north wing houses four offices and one meeting area.

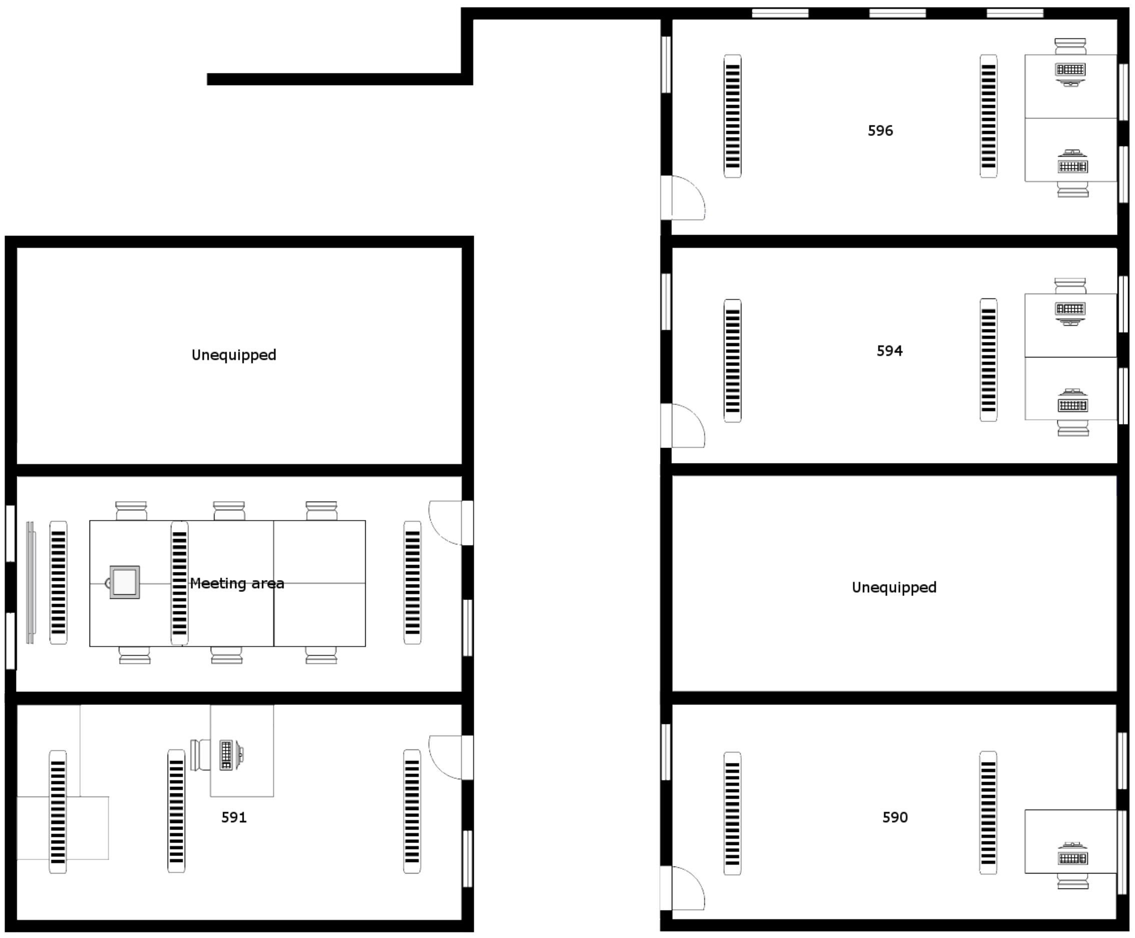


Figure 4.2: Map of the offices and meeting area on the north wing of the fifth floor.

4.1.1 Kitchen area

The kitchen area is a common social area where office workers mostly meet during lunch breaks to use the microwave or to get their food from the fridge. The kitchen has the following types of appliances that can be controlled:

- 1x fridge.
- 1x water boiler.
- 1x microwave.
- 1x coffee machine.

4.1.2 Meeting area
The meeting area is a designated office for holding discussions and presentations. The meeting area does not contain any equipment except for a projector. The following types of devices can be controlled for the meeting area:

- 1x lighting fixture.
- 1x outlet strip (for portable devices).

4.1.3 Office
Offices are the most common areas and differ in size, shape, interior and occupancy throughout the building. Despite the different design the general usage remains the same and thus the following can be controlled inside an office:

- N computer and appliances, where N depends on the amount of workplaces and people in an office.
- 1x lighting fixture.

It is worth noting that the systems of the university, and the portable devices of the employees, run different operating systems. This is not only important in the case of putting computers in standby but also for the implementation of the Green Mind system itself because the system has to run on all the systems of the university.

4.1.4 Hallway
Hallways are the common entrance halls that run between the different areas. The hallways allow entrance to the offices, kitchen area and meeting area that are controlled by the system. In total there are two hallways being controlled, which are depicted in Figures 4.1 and 4.2. The following types of devices can be controlled for each hallway:

- 1x lighting fixture.

4.2 Architecture
The Green Mind system has been built out of loosely coupled components that each have their own designated tasks. These components need to work on the systems of the university, which consist out of different hardware and operating systems. The majority of the components were therefore written in Java because an easy to understand cross platform programming language was preferred and Java was already commonly used in the Distributed Systems group at the university. There are two exceptions, the backend of the Dashboard & Mobile App was developed in Python and the PC client was developed in C++ to eliminate the dependency to install Java on each system.

In Section 3.1 a design overview was briefly addressed about the components and basic architecture. The components will be explained in detail in Section 4.3, but first the overall architecture of the system is addressed in the order of the layers (bottom-up) that are shown in Figure 3.1.

4.2.1 Physical layer
All the different kinds of sensors and actuators are located in the physical layer. These sensors can be accessed through the sensor and actuator gateway (SAGW), which provides custom interfaces to all the sensors, so that the system can easily access the functionality of the actuators and sensors no matter the vendor or version of the hardware. Components in the physical layer only gather information from the sensors and actuators. They do not process the reading or send out commands by themselves, the components merely allow the higher layers to easily access the sensors and actuators. By allowing access to devices in the physical layer instead of

having higher components access them directly (e.g., through the use of shared software libraries or other common code for the individual sensor interfaces) it becomes easier to maintain and update the code of the interfaces without significant chances ending up with different kinds of implementations per component or that fixes are not being shared with developers of other components. Another reason to use a physical layer is that devices exist that can only be accessed through one physical location (e.g., a USB stick is required to access the connected devices) or accessed by one component at a time (e.g., a serial port connection that cannot be shared). The complexity of the diversity of sensors and actuators is also something that the developers of other components should not have to deal with.

4.2.2 Service layer

Components in the service layer use the functionality of the physical layer to provide added value for the higher layers. The service components provide functionality that exceeds the 'get and set' level of the physical layer and simplifies sensor and actuator access even further. Some components create new output themselves (e.g., when processing and converting the consumption data from the Plugwise devices), while others just process high level commands and translate those to commands that can be used by the SAGW.

4.2.3 Persistence layer

The persistence layer acts as a system wide long term storage. The data is stored by the components in such a way that it can easily be accessed in the future. The storage can also be used by components to store their state in, so that a component can always continue from the previous state if necessary (e.g., in the case of a hardware failure). The separation of the storage into the persistence layer makes it easier to manage the storage for all the components combined, instead of each component managing their own storage system. Another advantage of using one storage is the potential to increase availability and stability of the system by adding more servers, as it is possible that individual components will not expand their storage system unless absolutely needed (e.g., performance of an individual server becomes too low).

Figure 3.1 shows the persistence layer above the physical and service layer. Typically the persistence layer is one of the lowest layers because the only purpose is the storage and retrieval of data. Figure 3.1 differs from the typical order merely for the sake of keeping the design of the figure easy to understand while still showing all the connections to the storage. Based on importance and functionality the persistence layer could be placed at the same level as the physical layer.

4.2.4 Logic layer

The components belonging to the logic level are the high level components. These components use all the available data and functionality from the lower layers in order to make calculated decisions about the state of devices. This is also the layer where the system management components are located. Usually components in the logic layer have, or would benefit from, a full fletched graphical user interface as opposed to the lower level components where a console application suffices. Even though the input is coming from the lower layers to the logic layer, the processed data in the logic layer (i.e., output) will be used as input for the lower layers in turn.

4.3 Components

This section describes the function of the individual components from the different layers of the Green Mind system. All the components are loosely coupled, which means that components can operate independently of each other. The added advantage is that the other components can remain running if another component fails (or wait until the failed component is online again). Loose coupling also means that components find each other at runtime as opposed to static compile-time binding. The components communicate through a common message topic to make it easier to replace components or to run multiple instances in the future (e.g., if a single component becomes a bottleneck). Communication between the components is done with a Kafka message queue which is accessible by the components through ZooKeeper. The communication is further discussed in Section 4.4.

4.3.1 OrientDB

After careful consideration (see Section 3.2) OrientDB was picked as the main storage facilitator for the whole Green Mind system. For some components is communication not enough and the data they create is not only important at the moment of creation but also for later reference (e.g., for research or presentational purposes). This historical data needs to be stored in a central place so that other components can also access this common data without the help of communication from other components. By relying heavily on other components the chance of losing data increases because when there are more components there are also more possible points of failure. By providing a storage system (especially with data replication, such as OrientDB, to increase reliability and availability) it is not always necessary to go through the different components to gather the required data.

A good example of important data is the indirect cooperation between the consumption component and the dashboard & mobile app component. The dashboard & mobile app component uses the gathered data from the consumption component to present the user with graphs and other statistics about the energy consumption. Instead of having the consumption component communicate all the new consumption measurements to the dashboard & mobile app component directly (which would then also need to store it somewhere to show historical data), the consumption measurements are stored in the database directly. The dashboard & mobile app then retrieves this data from the database on request.

Other data that is also stored in the database are the rules of the controller component, the variables of the context component, the sensor list that is maintained by the SAGW and user management of the dashboard & mobile app component.

4.3.2 Sensor and actuator gateway

Sensors and actuators are an important part of the Green Mind system. Without the sensors there is no data for components to base their decisions upon and without actuators it is not possible to influence the energy consumption. A big concern with the sensors and actuators is that they return different types of values and that the method of retrieving those values differs per vendor. On top of that do the sensors and actuators often not easily interact with software and require extra effort is to easily interact with them (e.g., through Java). Because the Green Mind system is currently a research framework in particular, with the initial implementation running at the University of Groningen, it is almost certain that different hardware will be added in the future.

The SAGW is designed to generalize and simplify access to sensors and actuators for the other, high level, components. Low level communication, such as serial communication with the Plugwise devices, is implemented in different interfaces which the SAGW uses to execute the commands and requests from the other components. The SAGW also converts any encoded values, such as hexadecimal representations, to useful values because conversion often depends on the implementation of the sensors and actuators and higher level components should not be bothered with this conversion. Instead of the high level components communicating with a specific component of each specific sensor (which is likely to change in the future), they communicate with the SAGW only. The main advantage is that only a new interface has to be added to the SAGW when a new sensor is added, making sensors a lot easier to manage. For the Plugwise devices a completely new implementation was written in Java to be able to turn devices on and off, as well as retrieving the consumption information for all the available devices.

The sensors or actuators for the SAGW are also not limited to hardware only. In the case of the sleep management server (SMS) component it was necessary to run a small piece of software on the workstation computers to determine if a computer was being used (active or idle state) or to put the computer into another state (on, sleep, hibernate and off). The abilities of the software installed on the workstation computers are handled by the SAGW just like any other actuator.

Components communicate with the SAGW through a Kafka message queue and JavaScript Object Notation (JSON) objects. JSON is text-based and designed for human-readable data interchange. REST would have been a valid alternative for communication between the components, but a message queue has several important advantages compared to REST (e.g., allows for better scalability, can persist the messages that are sent, allows clients to receive pending messages after a failure [184]). Kafka easily integrates with ZooKeeper and also allows the SAGW to easily communicate to multiple components, which is especially useful when other components also need to be notified when the state of a device changes (e.g., the context component can be notified instantly when the orchestrator component changes the state of a device) to eliminate the need for polling the state of devices continuously.

4.3.3 Consumption measurement

Plugwise devices are used to measure the consumption of devices or to turn connected device on or off. Each Plugwise device has three different buffers that contain consumption data:

1. A 1 second buffer that contains the energy consumption of the last second.
2. A 8 seconds buffer that contains the energy consumption of the past 8 seconds.
3. A history buffer that stores the energy consumption per hour for more than a year.

An older and smaller research project at the University of Groningen [188] retrieved the one and eight seconds buffers at a fixed interval, but in the larger office environment this turned out to be impractical due to the extra processing time needed for the larger amount of Plugwise devices. The latency of the Plugwise Zigbee network also increased due to the increased spread of the Plugwise devices relative to other Plugwise devices and the architectural obstructions between the Plugwise devices. Plugwise also notes that the one and eight seconds buffers are not as reliable as the hourly intervals and the hourly intervals should always be preferred for precise measurements.

The consumption component uses the history buffer instead of the one or eight second buffers to limit the network traffic and processing load. Upon request, the log address of the log that contains the desired hour (e.g., the previous hour) is passed along. Each log address points to four entries of an hour (e.g., when requesting the consumption for 14:00 a response could contain 11:00, 12:00, 13:00 and 14:00, depending on the log address used for the request). The consumption component requests the historic data once every hour from the SAGW and continues retrieving entries until the last history entry that is stored in the database is reached.

By requesting all history logs until the last log that was stored in the database it is also no longer an issue when the consumption component fails, the Plugwise devices will continue to monitor the energy consumption and when the consumption component restarts it will simply gather all the missing data. The same also applies when the network of the Plugwise devices is temporarily unreachable. When the network connection is reestablished the consumption component will retrieve everything until the last stored history log in the database.

Even though the consumption component works closely together with the SAGW to retrieve the consumption measurement data, it is not part of the SAGW. Retrieved data needs to be correctly stored in the database and old or missing history log entries also need to be retrieved. This added data management is not part of the SAGW and thus are the energy consumption measurements handled by this separate component.

Plugwise stores data in the form of an amount of pulses, which can be converted to the corresponding watts being consumed by the connected device(s). Figure 4.3 shows all the data in an hour entry that is returned by the SAGW after requesting the energy consumption of a Plugwise device. Most of the values are derived from the pulses and are stored to simplify processing for higher level components. Some sources [185, 186] indicate that the pulses should be corrected for both the current energy consumption and the historic energy consumption, whereas another source [187] indicates that the corrections are only used for the historic energy consumption. However, the software developed by the manufacturer (i.e., Plugwise Source) is only using the uncorrected values. As there is no definitive answer it was therefore opted to return both values to minimize problems with conversions in the future. All returned values are stored in the database to make sure that no data is lost.

```
{
        "address": "0D060E4C",
        "time": "2013-06-03T15:00:00.000+02:00",
        "pulses": 974116,
        "watt": 577.0219,
        "kwh": 0.57702184,
        "correctedpulses": 558222.6,
        "correctedwatt": 330.66562,
        "correctedkwh": 0.33066562
}
```

Figure 4.3: Content of an hour entry as returned by the SAGW.

4.3.4 Controller

The controller is the sole component responsible for providing the system with the ability to automate sensor and actuator behavior, which can positively affect the energy usage. Without the controller the system is not able to act upon the sensor and actuator variables but can only monitor and store the variables from the sensors and actuators. By adding a component to the system that can analyze the sensor variables and control the actuators it can read and change the state of the connected device (e.g., turn off a monitor in the weekend), and therefore achieve potential energy savings.

Because of existing experience in the Distributed Systems group, the desire to dynamically add new commands without the need to recompile, and the variations of user preferences (e.g., some users like their offices dark) the decisions was made to develop a rule-based controller that uses a format that is easy to read and write. These rules provide the ability for the system to act upon the sensor and actuator variables (e.g., in the weekend all computers should be turned off or be in hibernate).

Because the rules are to be parsed, evaluated and executed the decision was made to use an expression language to facilitate the querying and manipulation of Java objects at runtime. MVEL [199] was chosen after careful consideration between several other expression language:

- ANTLR [189], which always requires a separate executable [194] and is mostly developed for tree-based language recognition [189].
- Jep [190], which is only available as a trial version [195].
- JUEL [195], which has no active development [197] and low performance compared to MVEL [192].
- OGNL [191], which has low performance compared to MVEL [192].
- JEXL [193], which has no active development [198] and low performance compared to MVEL [192].

MVEL provides the controller with the ability to evaluate the rules with nearly the same performance as regular Java code and also provides a list of powerful features suitable for parsing, evaluating and executing the rules (e.g., projections, folds, property navigation) [200].

The variables that the controller received from the context can be used in the rules. A variable contains a type (e.g., computer), an identifier (e.g., 127.0.0.1), a name (e.g., is_idle) and a value (e.g., false). A list of all variables and their state is initially send to the controller by the context the moment the controller is started, whereas only the changes of the variables are send by the context afterwards. Variables from the same type are grouped together (e.g., computers) for easy access by the rules. The controller itself provides one additional variable that is not received from the context, namely a *date* variable. The date provides the rules with the ability to use the day, month, year, hour, minute, isweekend and isweekday in their evaluations.

Through the context variables the rules can act immediately upon changes from the sensors and actuators. In Figure 4.4 an example is depicted of a simplified rule, whereas Figure 4.5 depicts an example of an extended rule. To distinguish between a simplified and an extended rule, the rule has to start either a # or an @.

```
#(misc['date'].get('hour') >= 20 && computers['127.0.0.1'].get('is_idle') == true =>
computers['127.0.0.1'].set('state', 'off'))
```

Figure 4.4: Example of a simplified rule to turn a computer off when it is idle and it is after 20:00.

```
@(Weather weather = new Weather(); if (weather.getWeatherFor('Groningen') == Weather.Cloudy) {
lights['LIGHT_1'].set('state', 'on'); })
```

Figure 4.5: Example of an extended rule to turn a light on when the weather is cloudy.

The simplified rules are based on a predicate, the expressions before the first =>, that should evaluate to *true* before the remaining part (the expressions after the first =>) of the rule is evaluated and executed. The variables that are set in the remaining part of the rule are immediately sent to the orchestrator after the rule is evaluated and executed. Figure 4.4 and 4.7 only show examples of a single device, but it is also possible to create a rule for a whole group, (e.g., a rule for all computers. Because the simplified rules are using a predicate to determine whether or not the remaining part of the rule should be executed, it is possible to improve the performance of such rules by determining which specific types and identifiers are used in the predicate. For example, it is not required to evaluate a predicate of a rule that only uses computer['10.0.0.1'] when a variable change for computer['127.0.0.1'] is received from the context. All in all, the simplified rules provide the users with an easy and fast way to act upon the sensor and actuator values to positively influence the energy consumption.

The extended rules are direct Java code and provide the users to create rules that go beyond the possibilities of the simplified rules. The extended rules do not feature a predicate and are always evaluated after a variable change is received from the context due to the sheer amount of expression possibilities. However, the ability to execute direct Java does impose a security risk that is not present with the simplified rules. Depending on the need for more complex rules, and the gains in energy saving potential of such rules, the use of extended rules could be justified to provide more possibilities to increase the overall energy saving potential of the system.

Each time a new rule is added to the controller it is automatically stored to the database. After the controller is restarted the rules are retrieved from the database and it is determined which rules use which variables in order to improve performance for when variable changes are received from the context. The flexibility of the rules provide the Green Mind system with the ability to achieve potential energy savings by acting upon the sensor and actuator variables that are send by the context. The output from the controller is sent to the orchestrator, which in turn will send a message to the SAGW or the SMS based on the input of the controller.

4.3.5 Orchestrator

In order to keep the controller as simple as possible the execution of the plans made by the controller is left to the orchestrator. The orchestrator component acts a buffer between the physical layer and the controller and takes care of sending the commands at the correct time, as well as the order of execution. Each plan can be started and stopped at any time, or paused and resumed if necessary. To limit the chance of the orchestrator component becoming a bottleneck, the orchestrator is multithreaded and implemented in such a way that multiple instances of the orchestrator can execute simultaneously.

The orchestrator communicates with the SMS and SAGW, depending on the instructions received from the controller. The SMS handles the requests from the orchestrator to change the state of workstations and the SAGW handles the state change requests for the other devices. The current state change requests are straightforward and consist out of a unique identifier for the device (e.g., a MAC address, IP address) and the desired status of a variable. The status can be *on*, *off*, *sleep*, or *hibernate* in case of the workstations for the SMS, whereas the possible statuses of a variable depend on the type of the device for the SAGW.

4.3.6 ZooKeeper

Not all the components of the Green Mind system are running on the same computer. One reason can be because of hardware limitations and another reason is the importance of the geographical location (e.g., making sure that the person responsible for maintenance is as close to the system as possible for direct access).

Each component registers the IP addresses and ports used with ZooKeeper at startup. ZooKeeper allows components to find each other without the need to know the IP address of each other, which reduces the amount of configuration necessary for each component. ZooKeeper also makes it easy for a component to find out if all components are up and running because a component does not have a ZooKeeper entry anymore after it fails. Integration with ZooKeeper greatly simplifies maintenance and automates discovery of the other components. Another advantage is that Kafka uses ZooKeeper out of the box as well for the same purpose. As Kafka also has the ability to connect to a remote ZooKeeper installation, instead of using the shipped installation, only one installation is required for both Kafka and the components of the Green Mind system.

4.3.7 Other components

Because of the scale of the system some of the components (i.e., context, SMS and dashboard) were implemented by other teams. The tasks of these components in the Green Mind system are discussed in this subsection.

Context

Sensors and actuators are mostly limited to one simple task (e.g., a PIR sensor is either true or false when there is movement). A common problem in the Bernoulliborg building is that the lights in the offices also contain such a PIR sensor, which means that if an employee is working quietly at a desk the sensor will not detect any movement and will turn off the lights. The task of the context is to avoid such problems by creating a completely new variable by combining values from multiple sources. In the case of the lights this could mean that a new variable is created called *RoomOccupancy*, which is set according to the activity readings from both the computer client and the PIR sensor. This means that when the PIR sensor does not register movement and the computer is still being used the lights will remain on. The variables generated by the context expand the possibilities of the system even further by creating valuable additional information from the sensor input.

The context either requests or receives a notification about the changes of the sensor and actuator states through the Kafka message queue. These states are then processed by Twitter Storm to form the new context variables through a predefined truth table. The variables, both processed and original, are stored in the OrientDB database and are also passed on to the controller.

SMS

The sleep management server component and the SAGW computer client were developed together. The computer client runs on any workstation and exposes certain abilities from the computer to the Green Mind system. Besides a value to indicate whether the computer is active or idle, is the possibility to put the computer to sleep, hibernate, on or off included in these abilities.

The workstations and their states are managed by the SMS. When a state changes of a computer client then the SMS will communicate with the context component by sending out a notification that the context variables need to be updated accordingly. Other components (e.g., the orchestrator) can instruct the SMS to change the state of a given computer, but also request information about the computer from the SMS if necessary.

The SAGW computer client was developed in C++, as opposed to Java for the other components, because when C++ is used for development there is no need to install the Java dependency on each workstation. This provides a faster, easier and better manageable solution that also adheres to the ICT security policy of the university of Groningen.

Dashboard

To raise awareness and decrease energy consumption as much as possible it is important to provide feedback or to create a social element. All the visualizations of the Green Mind system are handled by the dashboard. Employees can view their consumption online or through a mobile app. The dashboard and mobile app component is larger and has more diverse tasks than most of the other components. It handles both the authentication for remote viewers and also serves all the different presentational formats to the users on the different device types (e.g., public display in the building, applications on mobile phones).

Even though an employee can view the energy consumption of his own workstation, for a public display in the building it is not desired to single out a specific user. With the data model used in the database for the energy consumption (i.e., a user is located in a room and that room in turn belongs to a floor of a building) it is possible to change the detail of the data. For public displays the dashboard will use a more general representation such as energy consumption on a per floor or per building basis.

4.4 Communication

All the components in the Green Mind system communicate with each other through the use of JSON objects. JSON was picked because of the good readability, simple syntax and ease of use. JSON is also less verbose than alternatives like XML, which decreases the size of the message payloads.

Developers of components that communicate with each other dictate the content of the messages that are communicated with each other. Depending on the data that the component requires the body of the JSON object may change. For the sake of traceability with asynchronous communication and readability and consistency in generic messages, a basic template was specified to which all the messages of components should adhere. This basic template is depicted in Figure 4.6.

```
{
	"id": "7FB0A415-7AED-440F-A4D7-EDFEB299ED2C",
	"data": {
		"method": "requestdevicestate",
		"parameters": {
			"mac": "000D6F000098C09E"
		}
	}
}
```

Figure 4.6: JSON object of a typical request.

Each request that a component sends should have an id by which the message can be uniquely identified. In the case of the request in Figure 4.6 the id consists of a regular Globally Unique Identifier (GUID), which is a unique reference number that can be used as an identifier. The id field can be used to couple request and response, which is especially useful in cases where communication happens asynchronous. As a message queue is always asynchronous the id field is mandatory to trace the response back to a request.

```
{
	"request": "7FB0A415-7AED-440F-A4D7-EDFEB299ED2C",
	"status": "success",
	"data": {
		"mac": "000D6F000098C09E",
		"state": "on"
	}
}
```

Figure 4.7: JSON object of a typical successful response.

When a component responds to a request it reuses the original id from the request and places it into the request field of the response object. There is also a status field that indicates whether the component was able to correctly process the request or not. Figure 4.7 and Figure 4.8 depict an example response message, with a successful and an error status respectively.

```
{
        "request": "7FB0A415-7AED-440F-A4D7-EDFEB299ED2C",
        "status": "error",
        "data": {
                "code": 123,
                "message": "PlugwiseDevice is not set to an instance of an object."
        }
}
```

Figure 4.8: JSON object of a typical error response.

In the case of Figure 4.7 the component correctly processed the request and returned all the available data. Figure 4.8 shows a JSON object for when the request fails or an error occurred. Instead of returning any of the requested data, the JSON object contains a specific error code and a message that describes the problem. The code field is internally unique for a component (e.g., code 1 might mean *invalid parameter* for one component and *could not find device* for another), but cannot refer to more than one specific error. The status field can have one of the three states listed in Table 4.1.

Type	Description
success	All went well and (optional) data was returned.
fail	There was a problem with the submitted data/parameters.
error	An error occurred while processing the result.

Table 4.1: The three available values for the status field in a response JSON object.

4.5 Discussion

The Green Mind system has been implemented in the course of about six months and the required components are accounted for. However, at the moment of writing the system as a whole is only partially operational, which can only be solved by further development of the partial finished components. The components in question are the SAGW, of which basic functionality is operational but only as a temporary standalone component rather than the desired form as discussed in Subsection 4.3.2, and the context component, which is unable to communicate with other components but can process variable changes and update the context variables accordingly in test situations. These components were co-developed by two other groups that were unable to finish the components in the time slot of this thesis.

Although it is currently not possible to test the Green Mind system over a long period of time to determine whether it is able to lower energy consumption completely autonomously, the Green Mind system has already been gathering consumption data for weeks and is installed and functioning in the offices. All the sensors and actuators can be accessed through the software. The controller has been successfully tested with a dummy context component and with that the rest of the system functioned as dictated by the architecture design. Automation cannot function due to the incomplete SAGW and context components, but the purpose of designing and building a system that is able to actually function in offices has been met.

By installing the Plugwise devices, that function as both sensor and actuator, the Green Mind system can reach all the necessary sensors and actuators through the wireless ZigBee network. The computer clients also communicate through the local TCP network and also require no additional infrastructure to be installed, as was intended. The computer clients even function as very cheap occupancy sensors because most of the work being done in the offices involves a workstation one way or another. These basic actuator and sensor capabilities, combined with the knowledge of the time of day, already makes for a system capable of saving energy in the Bernoulliborg building. Workstations can be turned off at night and in the weekend. Lights can be turned off during the day while normally the built-in motion sensor of the office lights would still turn the lights on, even if there is enough sunlight available.

The sensor capabilities of the Green Mind system are currently somewhat limited, but the SAGW provides the possibility to add more sensors over time. The current system would mostly benefit from a light illuminance sensor and a better means to detect occupancy. The light illuminance sensor would allow the system to better manage the lighting in specific rooms according to the available sunlight, instead of only relying on the time of day and occupancy. A big drawback of such sensors is that commercial solutions are rigid and expensive. The current viable occupancy sensor is cheap, but has some drawbacks (e.g., no location and amount of occupants, and are all delay-based) that limit the potential energy savings. The investment for all offices is large, especially without proper research into the kind of sensors and their effectiveness (e.g., what is the correct positioning of such sensors and which value ranges should be supported). For an implementation with the scale such as the Green Mind system it might even turn out that home built sensors are able to provide a better and cheaper solution. The main concern is that installing all kinds of sensors is expensive and potentially unnecessary. If done correctly the installation and choosing of the sensors is a whole separate research project.

All in all the Green Mind system is capable of reaching the goals set out in the introduction. Both lighting and devices can be monitored and controlled. The Green Mind system is a framework that allows the University of Groningen to expand its research into sustainability in new direction, such as user awareness, and provides the researchers with real and up-to-date data. The loose design of the system components means that it can be enhanced over time, exceeding the goals of this initial design, and thus provides more possibilities than the existing built-in BMS.

Chapter 5

Theoretical results

Chapter 5 presents the collected energy consumption measurements from the Green Mind system in the office environment that was discussed in Section 4.1.

First, the measurements are presented as is in Section 5.1. The measurements presented in Section 5.1 are without the system's ability to automatically influence the energy consumption. Using the gathered energy consumption measurements the estimated energy saving potential of the system is discussed in Section 5.3 based on the current functionality of the Green Mind system. These potential energy savings are also compared to previous work in Section 5.2.

For cost calculation the price of €0.07 per kWh will be maintained [201]. The cost of an individual Plugwise device is €33 [202]. Working weeks consist of 40 hours, 8 hours per day, and 5 days in the week, totaling to 228 workdays [204] per year (after holidays). This leaves 128 hours per week (24 hours a day and 7 days a week, minus 40 working hours) that are outside office hours.

The Bernoulliborg building is operated from 7:30 to 20:00, which is based on the measured time that the corridor lighting is turned on. Public area equipment (e.g., coffee machine, microwave) is expected to be online for the total 12:30 hours, which leaves a remaining 11.5 hours per day that the building is considered empty. For a whole week this results in 105.5 hours (11.5 hours per day for 5 days per week, plus 24 hours per day for 2 weekend days) that are outside office hours.

5.1 Consumption measurements

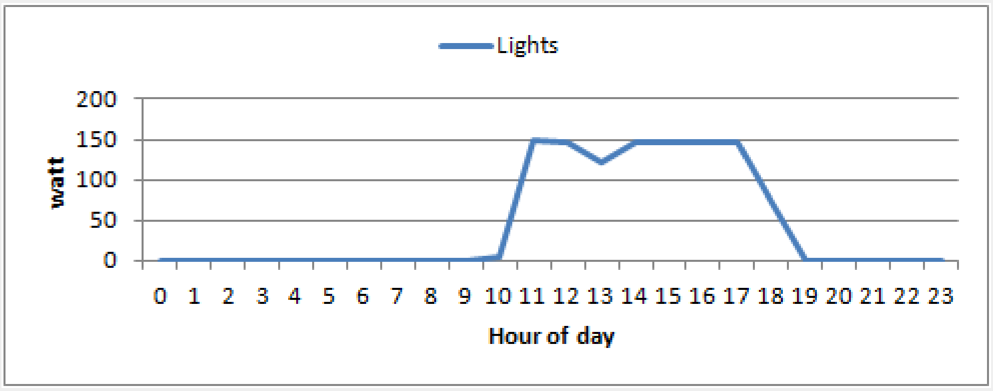
Over a course of six weeks, from mid-May to late July, the office environment on the fifth floor of the Bernoulliborg has been monitored 24 hours a day and 7 days a week. Measurements are divided into two segments. The first segment consists out of the devices located in the offices. These devices and their consumption depends on occupancy of the offices and the usage of the devices by the staff that is located in that specific office. The second segment consists out of the devices that are common goods. These devices are used by multiple people and mostly remain active throughout the day, even without people being present (e.g., hallways are always lit).

5.1.1 Offices

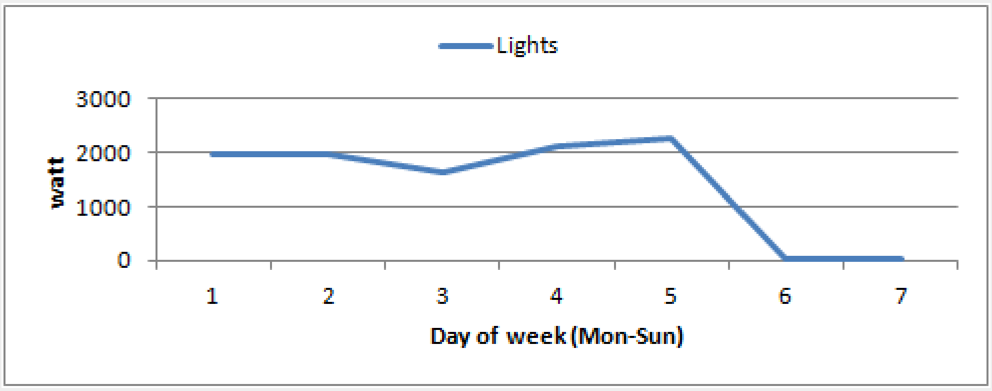
Two types of devices are measured in offices. There are the lights, which are grouped together to a single Plugwise device, in case of multiple fixtures, and the workstations which have one Plugwise device each. Due to modern monitors already having a low energy consumption in standby mode, as discussed in Subsection 3.2.2, it was decided to group the computer, monitor and any auxiliary devices in a power strip that is connected to the workstation Plugwise device. The Green Mind computer client can put the computer into sleep or hibernate mode. The Plugwise device only needs to be used as an actuator if it is desirable to eliminate any remaining standby power consumption of the workstation completely.

Light

Measured between 75-225 watt (75 watt per fixture).



Common consumption pattern of two combined light fixtures in the course of one day.



Common weekly consumption pattern of two combined light fixtures in an office.

Notes:

- Maximum of three light fixtures per office.
- Fixtures already contain a PIR sensor and cannot be manually turned on or off.

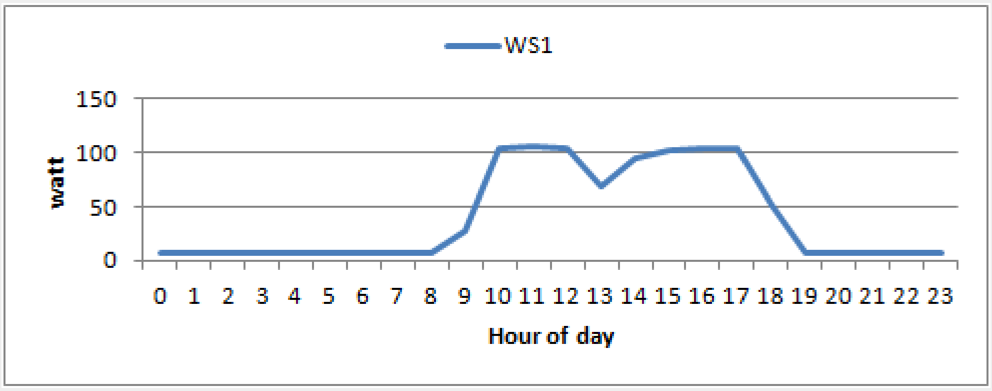
Figure 5.1: Energy consumption summary of office lights.

A summary of the energy consumption of the lights in the offices is given in Figure 5.1. Important items to note are that the monitored offices have at least two and at most three separate light fixtures. These fixtures are already controlled by a PIR sensor in the office. This PIR sensor could not be used by the Green Mind system and thus the Plugwise device was installed on top of the fixtures and the PIR sensor. This means that even though the Plugwise device is turned on, the PIR sensor still needs to register movement for the lights to work. It is not possible for the office workers to turn lights on or off manually. The effects of the PIR sensor are also represented in the two graphs of Figure 5.1. Most noticeable at night and in the weekends where the lights do not consume any energy, but also on regular weekdays where the lights stay on all day (even when the sun is active) because there is movement in the office.

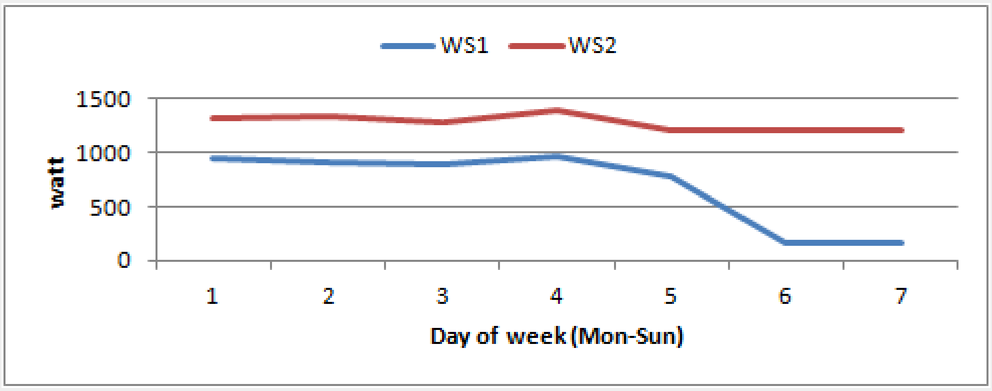
A single fixture consumes around 75 watt when turned on. This means that the lighting of a single office consumes 150-225 watt per hour for around eight hours. This equals to around 1200-1800 watt per day that is simply being wasted on a sunny day. The PIR sensor alone is not enough to save energy. With an average of 4.5 hours [203] (56% of the eight hours of work time per office) of sunlight per day and 228 workdays per year the annual savings could amount to 153.9 kWh to 227.81 kWh per office annually.

Workstation

Measured between 15-220 watt.



Common consumption pattern of a workstation in the course of a day.



Common weekly consumption pattern for an office workstation.

Notes:

- Researchers sometimes use their workstation to run experiments.
- Common workstations still use 7-10 watt when turned off.
- Workstations are measured through a power strip that contains the computer and monitor(s). This power strip might occasionally contain extra office appliances.

Figure 5.2: Energy consumption summary of workstations.

Workstation energy consumption is more irregular because of staff having different needs. Some workstations contain better hardware in order to run research projects, some staff members prefer dual monitors, and some staff member use their laptop (sometimes with an external monitor). This means that the energy consumption ranges from around 15 watt for a small laptop to 220 watt for a dual monitor research workstation.

The top graph in Figure 5.2 shows the hourly consumption of a standard university issued computer, which peaks around 167 watt when all processing power is being used. On average the consumption is just above 100 watt. The slight dip around 13:00 is most likely caused by the staff member going out for lunch and manually turning off the monitor and/or computer for the duration of the lunch. Note that the workstation still consumes some energy outside office hours.

The week graph in Figure 5.2 shows the consumption of workstations throughout the week. Workstation 1 (WS1) is similar to the workstation from the top graph. However, workstation 2 (WS2) is used for research purposes and thus never shuts down, not even in the weekend. WS2 poses the problem that workstations for research are usually stocked with above average hardware to be able to process high workloads that usually requires more energy to do so. In the monitored office environment there are multiple machines that are powered on continuously, all belonging to the same research group. The Green Mind system could put these devices into standby mode when they are not being used, such as weekend and nights, but as those systems are used for research purposes this might not always be appreciated by the staff. Instead, it could be enforced as a university policy that only designated machines can be used for long term tasks instead of allowing every researcher to run his own local server or monitoring system. Note that the energy consumption of WS2 stabilizes in the weekend at the lowest energy consumption level, suggesting that the workstation is running but not actively used in the weekend. In some cases it could be sufficient for staff to be able indicate time slots where the workstation should be active. For example, in the case of a web server that is only accessed during work hours it would be sufficient to leave that computer running all day, even when the computer client indicates that the user is idle, but is put it in standby at night and in the weekend.

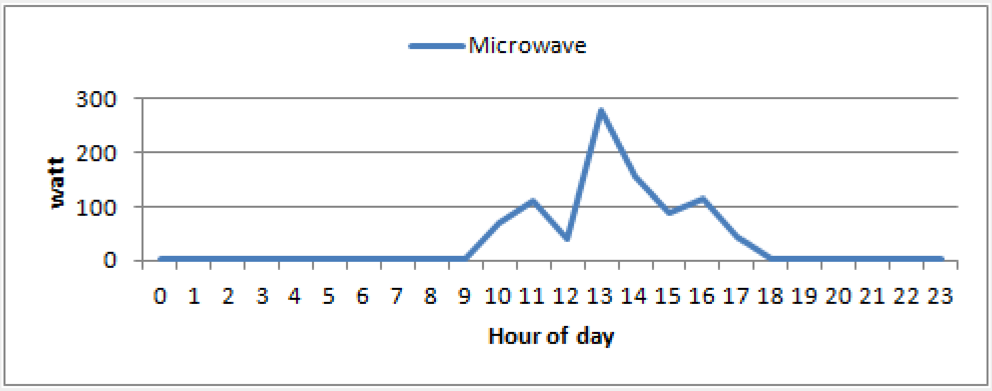
It is hard to pinpoint the amount of potential energy saving because of the amount of different hardware being used. University workstations still consume energy when they are turned off, but a staff laptop that is unplugged will not. When taking into account that a regular workstation still uses 7 to 10 watt per hour when turned off, it would mean that in a 40 hour workweek 7-10 watt is being consumed 128 hours per week per workstation for nothing. This comes down to approximately 1 kWh (22%) per workstation per week that can be saved by turning off the workstation completely at night and in the weekend.

5.1.2 Public areas

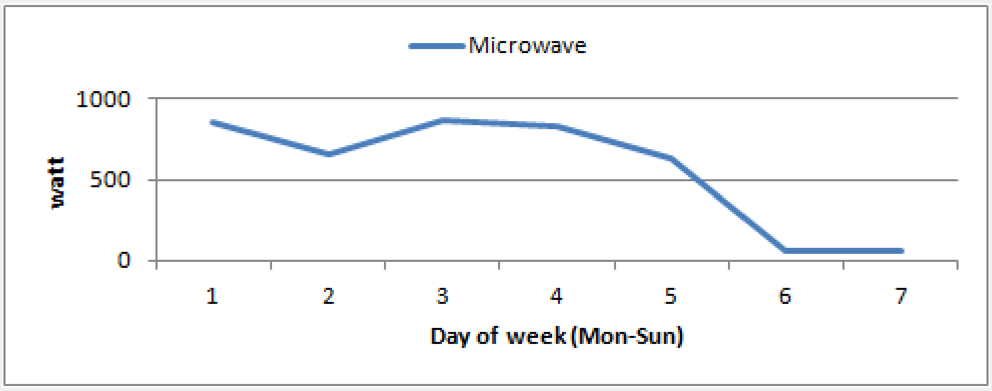
Public devices are located in the areas adjacent to the offices. This includes the light fixtures in the corridor and the appliances located in the kitchen area.

Microwave

Measured between 2.6-510 watt.



Common consumption pattern of the microwave oven in the course of a day.



Common weekly consumption pattern of the microwave.

Notes:

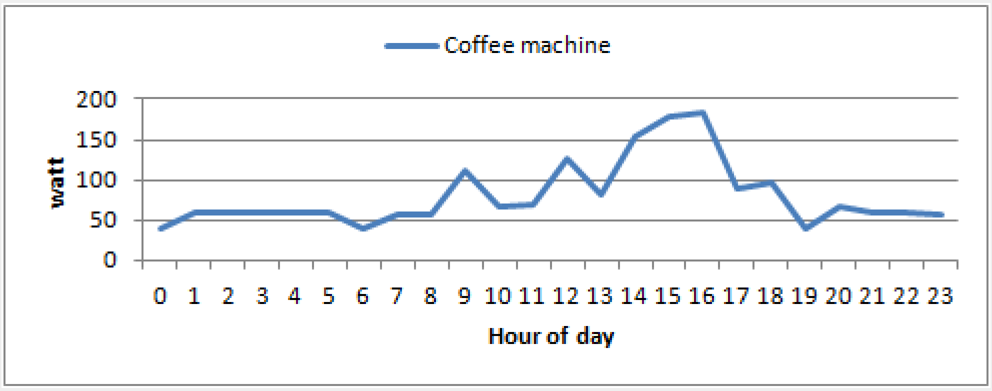
- Uses around 2.6 watt when idle.

Figure 5.3: Energy consumption summary of the kitchen microwave oven.

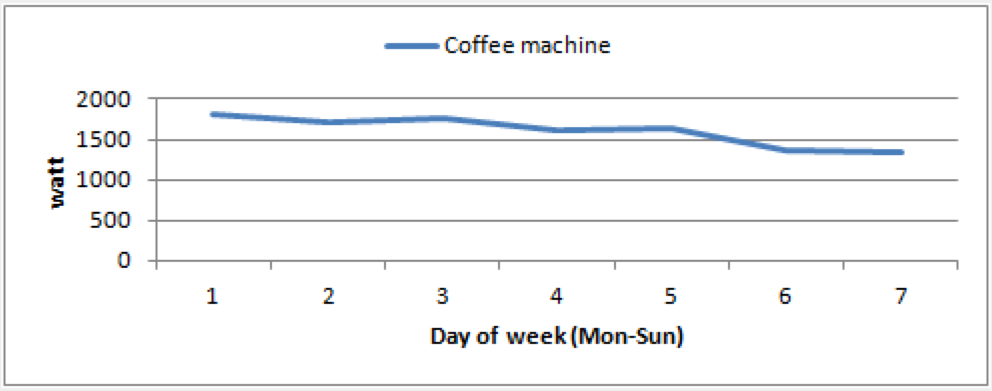
The microwave is used throughout the day and energy consumption peaks during lunch. Figure 5.3 shows the energy consumption of the microwave in detail. The energy consumption of the microwave can not be called excessive, around 2.6 watt is consumed when the microwave is idle. By turning the device completely off outside office hours around 274 watt (2.6 watt * 105.5 hours) can be saved per week, which still adds up to around 6% saving of its weekly energy consumption.

Coffee machine

Measured between 38-192 watt.



Common consumption pattern of the coffee machine in the course of one day.



Common weekly consumption pattern of the coffee machine.

Notes:

- Consumes 56 watt on average when idle.
- Turning it completely off might

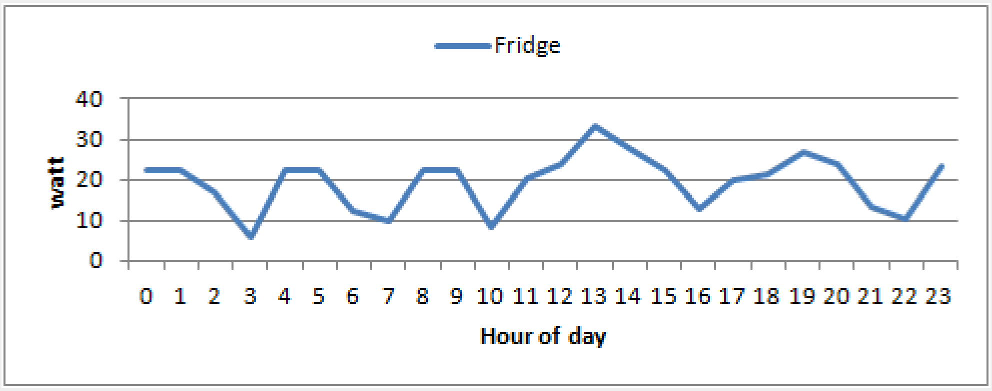
Figure 5.4: Energy consumption summary of coffee machine in the kitchen.

Coffee machines are common in offices and Figure 5.4 shows that the idle consumption of such a device is high, even when it is not being used. Most measurements were 58 watt, although roughly every six hours a measurement of about 38 watt occurs when the coffee machine was idle. Thus, on average the coffee machine uses 56 watt when there is no staff member to us it. There is no need for the coffee machine to be active outside office hours which means a potential energy saving of 5900 watt (56 watt * 105.5 hours) per week, which is around 50% savings of the total weekly energy consumption of the coffee machine.

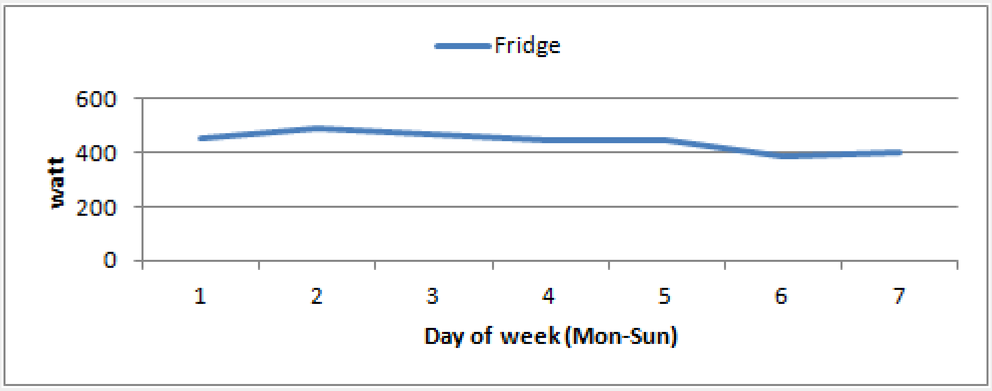
Potential issues with turning off the coffee machine at night and in weekends is that the machine might not be capable of recovering from long downtime. Besides the hardware limitations there might also be issues with the 'freshness' of the products stored inside the machine when the power is lost over longer periods of time. The fact remains that the monitored coffee machine consumes a substantial amount of energy at night and in the weekend. Judging by the recommendations by Bush et al. [205] regarding the energy efficiency of coffee machines it should be possible to disable the coffee machine completely.

Fridge

Measured between 3.6-291 watt.



Common consumption pattern of the fridge in the course of one day.



Common weekly consumption pattern of the fridge.

Notes:

- Consumes 16.6 watt on average when left undisturbed.

Figure 5.5: Energy consumption summary of the fridge in the kitchen.

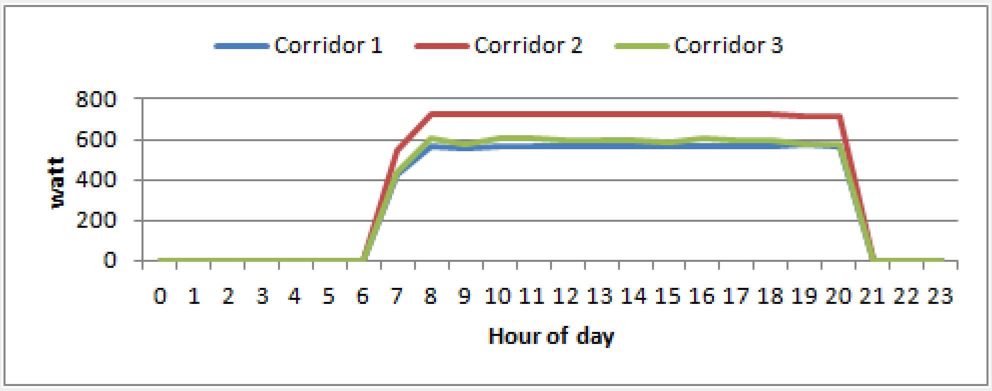
The fridge in the kitchen is used to keep drinks and the lunches of the staff cooled. The daily consumption shown in the top graph of Figure 5.5 shows that the fridge is cooled on intervals. Energy consumption rises during offices hour when staff opens the fridge and thus more cooling is required. Energy consumption peaks at lunch and dinner time.

The fridge cannot be turned off completely because the drinks and food in the fridge need to be cooled to stay fresh. Previous research by the Distributed Systems of the University of Groningen has shown that the fridge is capable of cooling sufficiently when only turned on for 15 minutes of every hour [22]. During these 15 minutes the fridge is cooling at the maximum energy usage. Taking into account that the rated consumption of the fridge is 70 watt, the consumption of the fridge during those 15 minutes per hour should be around 17 watt at most. This is nearly the same as our measured average of 0.166 kWh when the fridge is left undisturbed. As previous research in [22] also revealed that the cooling was sufficient even during the lunch hours, it would mean that our above average consumption of the fridge during office hours could be eliminated.

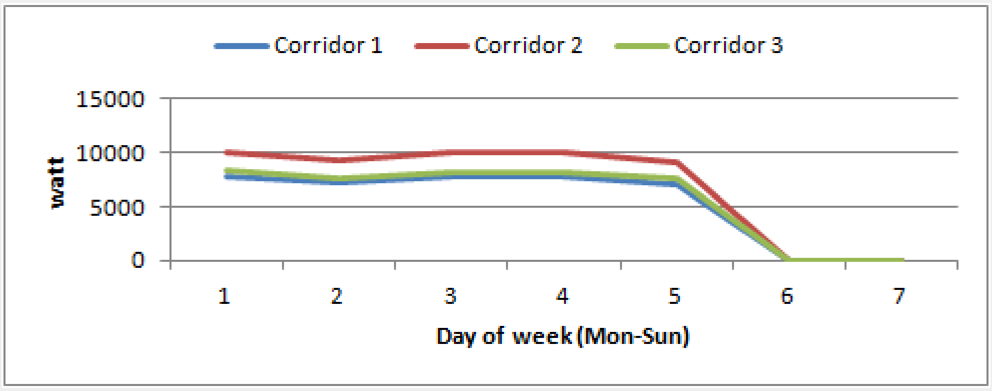
On average the daily energy consumption of the fridge is around 0.4 kWh watt (the energy consumption during the weekend in the lower graph of Figure 5.5) while during regular weekdays this amounts to 0.465 kWh. As a result, there is a difference of 0.065 kWh between a regular weekday and a day in the weekend. This would mean a saving of 0.325 kWh (5 days * 0.065 kWh) per workweek and a yearly saving of 14.82 kWh (228 working days * 0.065 kWh) per fridge, which amount to around a potential energy saving of 10%.

Corridor lighting

Measured between 560-755 watt (when on).



Common consumption pattern combined corridor light fixtures in the course of one day.



Common weekly consumption pattern of combined corridor light fixtures in an office.

Notes:

- Corridors are operated at building level and are only turned off completely (including the Plugwise device) at night and in the weekend.
- Light are turned on around 7:30 and remain on till around 20:00 (± 12.50 hours).
- Always on, not operated by movement like the office lights.

Figure 5.6: Energy consumption summary of lights in the corridor.

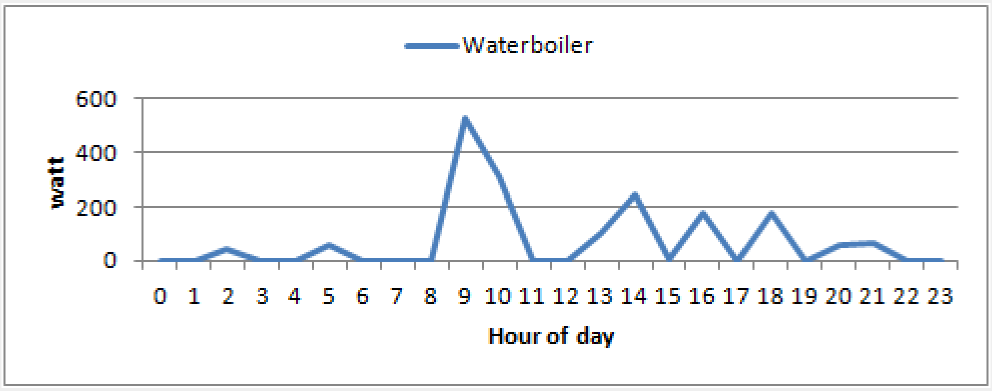
The two hallways of the monitored office environment are so large that the two hallways have been divided into three corridors with a Plugwise device monitoring the corresponding corridor. The hallway lighting has the same hardware as the office lighting but the hallway lights are not controlled through an PIR sensor. Lights are continuously lighting the hallways until they are turned off on a building level. As they are similar to the office lighting they also have the same flaw: on sunny days they remain turned on. Figure 5.6 shows the energy consumption of the different corridors. The consumption pattern of the corridors is identical but the amount of fixtures in corridor 2 and corridor 3 is slightly lower than the amount grouped into corridor 1.

Both hallways consume around 1900 watt combined when turned on. This means that on a sunny day each hour 1.9 kWh, in the monitored office environment on the fifth floor alone, could potentially be saved in energy consumption simply by turning the hallway lighting off. Taking into account that the hallway lights are continuously turned on when it is sunny outside there is a total energy saving potential of 1846.8 kWh (36%) per year, with an average of 4.5 hours of sunlight per day and 228 workdays per year.

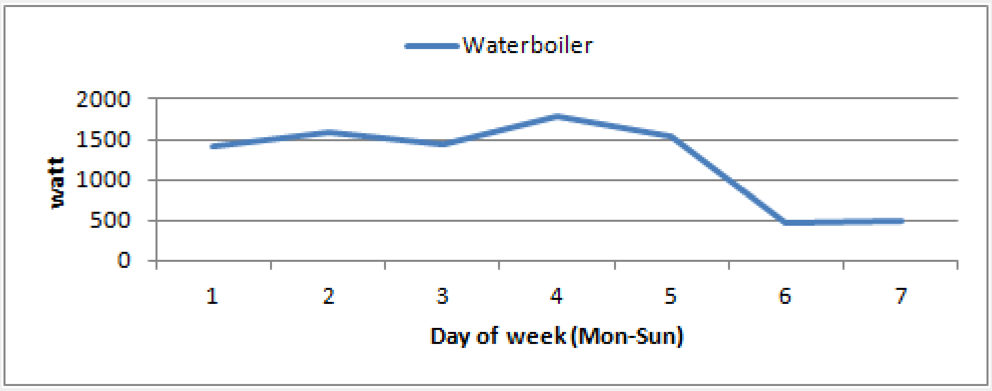
In some cases it might be desired to have more detailed control over the lighting so that it is possible to only turn on specific fixtures and partially light the hallway. For example, in the corner where the hallway in the east side of the building meets the hallway of the north wing there are no windows to let in sunlight and some additional lighting might be appreciated by some staff members whereas the rest of the hallways does not need any additional lighting.

Electric water boiler

Measured between 43-577 watt (when active).



Common consumption pattern of the water boiler in the course of one day.



Common weekly consumption pattern of the electric water boiler.

Notes:

- Does not consume any power when not heating.
- Consumes 20 watt per hour on average when left undisturbed for a whole day.

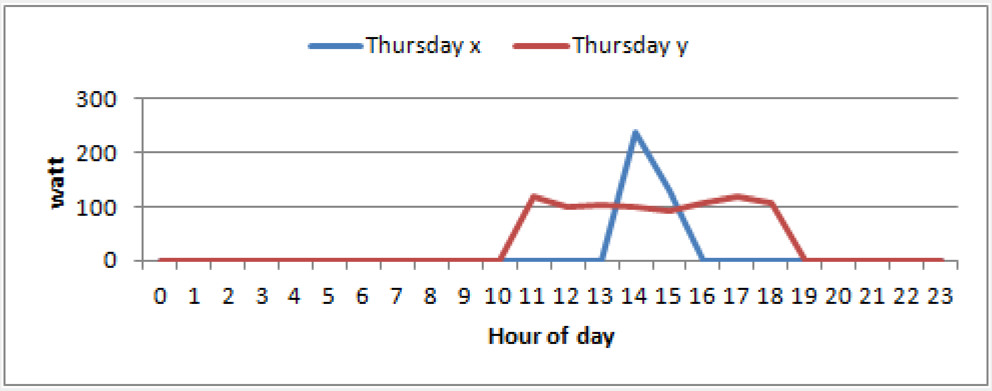
Figure 5.7: Energy consumption summary of the electric water boiler in the kitchen.

There is also an electric water boiler installed in the kitchen area. Figure 5.7 shows the consumption information that was measured for this boiler. The top graphs shows that the boiler uses power intermittently to keep its content heated. This is useful during office hours when there is need for instant hot water, but not so much at night and in the weekend when the building is empty. When no hot water is tapped from the faucet the boiler consumes about 20 watt per hour on average per day. This continuous consumption is clearly visible in the weekends where the consumption evens out at just below 500 watt per day, as visible in the lower graph of Figure 5.7.

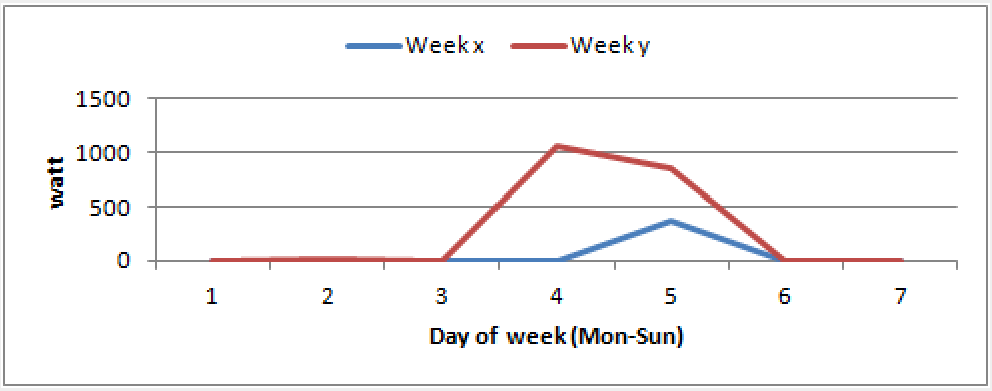
Energy can be saved by disabling the water boiler outside office hours. This would mean that 105.5 hours of consumption can be saved. It might take time for the boiler to reheat its content completely so starting before working hours might be necessary. This would still leave around 100 hours (roughly an hour is required, as depicted in Figure 5.7), which adds up to 2 kWh per week, 23% of potential energy savings.

Meeting room

Measured between 43-577 watt (when used).



Common consumption pattern of the meeting room in the course of one day.



Common weekly consumption pattern of the electric water boiler.

Notes:

- Beamer is unplugged after usage.
- No other appliances are present in the room.
- Usage is sporadic.

Figure 5.8: Energy consumption summary of the meeting room.

The meeting room does not leave much room for energy saving. There are no fixed devices and users bring their own laptops and a beamer for presentations and meetings. Usage is sporadic and unpredictable, as can be seen in Figure 5.8. On the individual days the users on Thursday *y* use more energy in a short period of time, but the users on Thursday *x* used the room for the whole day and consumed less per hour but more in total. Taking everything into account, the meeting room is an interesting location for monitoring the energy consumption but not for controlling the energy consumption.

5.2 Estimated energy saving potential and other research

In order to discuss the measurements, and the potential savings they entail when using the functionality of the Green Mind system over a longer period of time, Table 5.1 has been created to summarize all the findings. It should be noted that measurements were taken over a period of six weeks and not over a whole year. The *current estimated annual* values are calculated based upon the average energy consumption of the actual measured devices within and outside office hours during these six weeks, whereas the *after estimated annual* values are estimated only based on the possibilities of the Green Mind system to limit the energy consumption.

Device	Current estimated annual (kWh)	After estimated annual (kWh)	Potential annual savings (kWh)	Potential Savings (%)
Light - 1 office fixture	136.8	59.85	76.95	56%
Light - 1 corridor fixture	213.75	136.8	76.95	36%
Device - water boiler	397.73	284.09	113.64	28%
Device - fridge	160.82	146	14.82	9%
Device - coffee machine	592.21	261.25	330.96	56%
Device - microwave	208.37	190.25	15.45	7%
Device - 1 workstation*	224.73	173.9	50.83	22%

** Due to diversity only the standard university issued workstation is taken into account. Research workstations consume more power and are active 24 hours a day and 7 days a week, partial down time will at least equal or exceed the savings of a standard workstation.*

Table 5.1: Summary of the potential energy saving found through the measurements.

5.2.1 Lighting

As mentioned in subsection 5.1.2, the hardware of the corridor and office lighting is the same. This means that the potential savings are also the same when disabling the lights when the sun is out. For an office fixture this means that around 56% of the annual energy consumption can potentially be saved. For the corridor lighting this is only 36% because the building remains open for longer than the regular office hours and, unlike the office lighting, the corridor fixtures are not controlled by a PIR sensor. Corridor lights are thus turned on longer annually while the hours of sunlight are the same for both, resulting in less potential savings. The savings of 36% and 56% are substantial because they could be reached even when the installed fixtures already contain energy efficient lighting, and offices are even only enabled by motion sensors.

According to Boyano et al. [15] lighting is the highest contributor to energy consumption in medium climate zones, such as the Netherlands, at 50%. Through lighting control, such as taking natural light into account, they estimate potential savings for lighting to be 22% to 42% depending on the level of automation utilized. The proposed plan of energy saving through light sensors reached savings of 11% to 47% in a field study conducted in open-plan offices [206]. A large multi campus building experiment, by Sheng-Yuan Yang [207], with an energy-saving multi-agent system also managed to reach savings up to 20% for lighting.

5.2.2 Workstation

Based on the measured energy consumption of workstations that had been turned off, it should be possible to save 22% annually per regular workstation by cutting the power to these workstations completely at night and during weekends. For workstations it is only possible to estimate the potential energy savings for the remaining energy consumption when the workstation is supposed to be turned off completely. This is caused because there is no data about idle time available yet from the Green Mind system.

Other research that contained details about workstation energy savings mostly only focus on computers and incorporate multiple stages of energy savings such as disabling monitors, putting the computer into sleep mode and shutting down computers outside office hours. A study in Japan [8] showed that an average desktop computer consumed around 30% of its energy during idling, and 40% in non-business hours. On the other hand, there was the study conducted by Park et al. [208] that only showed an energy saving of 0.2% by setting the time of power usage or by using a motion sensor to control a laptop. The multi campus building experiment by Sheng-Yuan Yang [207] showed energy savings of 15% for computers.

5.2.3 Appliances

All the other measured devices are located in the public kitchen area, something that is present in most offices but not explicitly mentioned in detail by other papers. The fridge and microwave have an energy saving potential of 9% and 7% respectively. The measurements in [208] also include a microwave and the measured energy savings for that microwave add up to 3.3%.

For the coffee machine a potential energy saving of 56% is estimated, mainly because the high energy consumption of the machine outside office hours. The electric water boiler has the potential to save 28% of its energy consumption. Both suffer from the flaw that they do not enter a standby mode and thus keep heating water even without demand. No comparison material could be found for the energy consumption of the water boiler and coffee machine.

5.3 Discussion

In this section the measurements and estimations about potential energy savings from Chapter 5 are discussed in relation to the costs of the sensors and actuators and the usage of those sensors and actuators.

5.3.1 Reliability and applicability

Reliability and making predictions on energy consumption measurements is something that is always debatable. The implementation of the Green Mind system has been able to reliably measure the energy consumption of multiple devices over the course of six weeks. The next period of six weeks might differ because of all kinds of influences (e.g., temperate, sunlight, holidays). Even during these six weeks it became clear that the usage, and thus the energy consumption, can be irregular at times. This is especially so in the case of the energy consumption of regular workstations when compared to workstations that are being used for research.

Even with the irregularities the measurements and estimates are still applicable. By using averages, and taking into account the excesses, the estimated potential energy savings give a credible and applicable scenario that could be reached through building automation. There is no denying that the measurements presented in Chapter 5 show that there is still unnecessary energy consumed by all the measured devices. Especially with the motion sensors already being used by office lighting, it shows that more automation is necessary to increase the efficiency even further.

5.3.2 Lighting

The goal of lowering the consumption of lighting by 25% can easily be reached when turning lights off when there is enough natural light available. The estimations show that at least 36% can be saved. A potential problem with realizing these savings is determining the right amount of light sensors and placing them correctly in order to optimize the savings. The unique design of the blue facade of the building, which uses an external frame on top with partially printed transparent plates attached, might limit the incoming daylight. Light sensors and detailed occupancy models are necessary to form a better estimate. Judging by the similar ranges (11% to 47% [15, 206]) in energy savings from other papers, and in particular the 20% energy savings on lighting in campus buildings [207], it is safe to conclude that the goal of 25% can be reached.

The monetary savings are €5.38 (76.95 kWh * €0.07) per light fixture. When taking into account the goal to have a return of investment within seven years this would amount to the possibility to spend around €35 per fixture in sensor equipment. In most cases it is sufficient to group multiple fixtures together. For example, the current installation groups two or three fixtures, that are present in a single office, together into one Plugwise device. This leaves at least €37 (70 - 33) for the installation of one or more light sensors in the office.

5.3.3 Workstations

Research workstations consume considerably more energy than their regular counterparts and are mostly turned on 24 hours a day and 7 days a week. The estimation, in Table 5.1, of an energy savings potential of 22% per regular workstation does not represent workstations that are used for research because they are continuously turned on. When looking at the annual savings for all the workstations combined, including the research workstations, the potential energy savings are likely to turn out lower. On the other hand, the monitored offices belong mostly to the same research group and there are multiple research workstations active 24 hours a day and 7 days a week. Depending on the research it might be possible to combine some of these workstations. Only eliminating one of these research workstations would already save a considerable amount of energy. The decision to turn off a research workstation, or at least put in into sleep mode, is not something that the system can easily make on its own and requires input from the responsible researchers. Most likely the use of research workstation specific rules would be a good compromise. For example, a research workstation could be turned off at night but during the day (including weekends) the workstation is expected to be operational. The detection of such research devices at least provides building management the possibility to open such discussions with staff members to determine a reasonable policy regarding such devices.

For a regular workstation the monetary savings will be around €3.56 (50.83 kWh * €0.07). As the goal is to return the investment within seven years this would add up to around €24, which is not enough to cover the cost of the installed Plugwise device. Because saving on the remaining energy consumption if the workstation is turned off alone is not sufficient, and to reach the goals stated in the introduction, it is necessary to also execute additional algorithms to put computers into standby modes as fast as possible. Judging that 30% of the energy consumption is caused when the computer is idle [8] it should still be possible to reach the goal of 25% energy savings, especially when the research workstations get restrictions also. It should be noted that the idle time is handled by the computer client, which puts the computer into sleep mode, and thus the corresponding monetary savings do not change anything about the cost of the Plugwise device being too high.

Although the workstations on their own do not reach the goal of saving 25% of the energy consumption on devices, the savings of the workstations combined with those of the kitchen reaches the goal. From the workstations, nine could be classified as regular workstations. This would mean a total annual energy consumption of 2022.57 kWh (9 * 224.73 kWh) with a total estimated potential annual saving of 457.47 kWh. Combined with the measurements from the kitchen this would add up to 3381.7 kWh (1359.13 kWh for the kitchen, see Subsection 5.3.4) and an estimated potential energy saving of 932.34 kWh, totaling 27.5% on energy savings for all the devices combined.

When the research computers are also taken into account (with a total of 2848.58 kWh annually) then the potential energy savings drastically change for the worse. With a total energy consumption of 6230.28 kWh annually, the estimated potential savings for devices will only amount to 15% and thus miss the initial goal of 25%. On the whole building, the research to regular workstation ratio is lower and for the fifth wing of the Bernoulliborg it should definitely be encouraged to simply not run each research workstation 24 hours a day and 7 days a week just out of convenience.

5.3.4 Appliances

The measured appliances in the kitchen area can be divided into two categories, first there are the microwave (7% estimated potential energy savings) and the fridge (9% estimated potential energy savings). Both combined will save up to €2.12 annually, which gives a return on investment of 31 years for both their Plugwise devices. The potential savings do not justify the costs of two individual Plugwise devices for the fridge and the microwave. These potential savings are also hard to increase through further automation because the fridge simply needs to cool its contents and the microwave only has an idle consumption of 2.6 watt. The annual consumption of the microwave is not extremely high when compared to the other measurements, despite the high consumption of a microwave when active, because of the short time span necessary to heat its contents. In the case of the microwave a possible solution would be to use a single Plugwise device for both the microwave and the coffee machine because they have a similar usage pattern.

This leaves the second category with the coffee machine and the electric water boiler, which have estimated potential energy savings of 56% and 28% respectively. The monetary savings of the coffee machine will be €23 annually, and €161 within the goal of seven years. For the water boiler the annual monetary savings are estimated to be €7.95, adding up to around €55 within the seven year goal.

The solution of combining the coffee machine and microwave would mean that the microwave adheres to the powering schedule of the coffee machine, because the coffee machine needs to be active the longest per day. For the water boiler, the envisioned schedule is the same as the coffee machines so the boiler can also be added to the same Plugwise device to save costs.

Combined the appliances in the kitchen consume 1359.13 kWh annually, and have an estimated energy saving potential of 474.87 kWh. This means an estimated potential energy saving of 35% combined for all the devices in the kitchen, 34% when the savings of the fridge are left out of the equation, or 32% when both the fridge and the microwave are left out. Either way, the microwave is best included with the coffee machine and water boiler to at least also save some energy.

Chapter 6

Conclusion

The Green Mind system, that was designed and partially implemented for this thesis, showed that previous research conducted by the Distributed Systems group at the University of Groningen also scales to a larger uncontrolled office environment. The scale was not expected to be an issue but so was the cost of the system. As it turned out there is a lot of potential energy to be saved but tracking consumption of every single device is too expensive when using Plugwise devices. Each device is unique, but continuous monitoring is not always necessary. It is best to group devices together where possible. An automated building management system, such as the proposed Green Mind system, should be able to handle the repositioning of sensors and actuators and be installed in phases to optimize the cost-benefit ratio.

The first goal of lowering the energy consumption of lighting by 25% can be reached by measuring the available daylight and controlling the lights accordingly. The current use of motion sensors in offices to control the lighting is insufficient and leaves much room for improvement. The estimated energy savings range from 36% for corridor lighting to 56% for office lighting.

The second goal of lowering the energy consumption of electronic devices by at least 25% can only be partially satisfied due to the presence of research workstations that cannot save energy through simple automation. In the category of electronic devices the potential energy savings with the Green Mind system were 56% for the coffee machine, 28% for the water boiler, 22% for a regular workstation, 9% for the fridge, and 7% for the microwave. Most of the potential energy savings are below the said goal of 25%, but combined they average a potential energy saving of 27.5%. However, when the excesses of the research workstations, that are operated 24 hours a day and 7 days a week, are taken into account the potential energy savings are only 15%. In the specific cases of specialized research workstations, tailor made rules have to be designed in consultation with the responsible researchers in order to fully optimize the energy saving potential.

Costs of the implementation are limited to that of the hardware, such as new sensors and actuators. For this thesis the costs are created by the purchase of the Plugwise devices. The third goal of costs being returned within at most seven years is reached, mainly because of the annual energy savings per light fixture of an estimated €5.38. The cost of equipping every workstation with a Plugwise sensor is not justified in every case, but one has to take into account that the installation of multiple sensors does allow the localization of excessive energy use. By experimenting with (temporary) sensor and actuator placement, and creating different groupings according to the readings, the cost efficiency can be further improved.

The fruits of the thesis have provided the University of Groningen with numerous new possibilities for new research projects through accessibility to a live testing environment of actively used offices. A new modular system design has been introduced that allows for future incremental enhancements but is also able to operate outside a controlled experimental environment. The currently designed functionality, limited as it may be, is already capable of saving energy within the set goals. Through its loosely coupled component the energy saving potential of the Green Mind system is only expected to increase over time when old components are replaced with newer, more sophisticated components. By providing a framework that can be built upon, more time can be put in working out the details of individual components and less time worrying about the system architecture itself.

The estimates show that the following starting hypothesis is certainly true:

'Installing a building automation system that controls multiple occupied offices has the potential to save energy.'

A lot of interesting research is still to be done in the field of building automation and by having a platform such as the Green Mind system the University of Groningen is able to advance into the next stages of saving energy through automation.

Chapter 7

Future work

Although the results presented have shown energy saving potential by using component based automation, it could be further developed in a number of ways.

7.1 Extending and improving the sensors and actuators

In principle, the proposed sensors and actuators are able to provide the energy saving potential for the system. However, limitations on the proposed sensors and actuators have been discussed in Chapter 3. Perhaps by incorporating other types of sensors and actuators, such as RFID, NFC or WiFi tags to detect occupancy and user location, it is possible to obtain more accurate results and enhance the functionalities of the system. WiFi, RFID and NFC are all standards to establish communication between devices. It was also shown in Chapter 3 that custom built sensors and actuators are often cheaper than their retail alternatives. By exploring and selecting the correct sensors and actuators for a whole building the *benefit-cost ratio* of the system can be maximized.

Due to time constraints the subject of optimizing the type, location and number of sensors and actuators was only briefly examined. One of the questions that arose was the need for a light sensor in order to control the lighting better. But such light sensors are expensive. Are light sensors best placed at a window, per desk, per light fixture, or simply at the center of the room? Another good extension would be to make corridor lighting motion activated, but how many sensors would be needed, with which range and where should the sensors be placed? Questions about cost-benefit ratio and placement arise for most of the sensors and actuators, which justifies extensive research into this part of the system specifically. Closely related to the choice of sensors is research into the range and network latency of larger indoor wireless sensor or actuator networks.

The area of sensors and actuators clearly provides room for a lot of research into the combinations and placement of different sensors and actuators and their overall usefulness. Perhaps the most direct extension of this thesis is by the means of the sensors and actuators.

7.2 Comfort enhancement

In terms of functionality the system focuses on monitoring and reducing the energy consumption. As a result, it also affects the comfort of the user, both *positively* (e.g., no need to manually turn off the computer after working hours) and *negatively* (e.g., after a short break the computer is put to sleep).

A possible reason for the negative impact on the comfort is due to limited means of the system to accurately detect occupancy and location. Perhaps it is possible to limit the discomfort, or even increase the overall comfort, through the use of more or more precise sensors and actuators (e.g., automatically turning on the computer when the user enters the office). This could lead to a better user acceptance rate of the system.

Potential pitfalls are the impact of the implementation on the user's everyday routine. For example, making users carry along an tag (as described in Section 7.1) might solve the localization and occupancy sensing but might provide additional discomfort because the user might have to swipe the tag against a control surface every time when entering or leaving a room. A perk of the Green Mind system is that it does not require the user to do anything differently than without the system. The Plugwise devices and computer client do not require user interaction (no learning curve) and the system does not drastically influence the everyday flow when it is operational.

7.3 Testing the system, sensors and actuators

Although the system components were independently tested, testing the system components together uncovered several problems with the system, namely the unfinished SAGW and context components. Due to these unfinished components the remaining part of the system could only be tested for communication and basic functionality.

By finishing the SAGW and context components the system as a whole could be tested, not only for communication and functionality, but also for other aspects such as the stability and latency (e.g., between input from the SAGW and output from the orchestrator, or between other components). This advanced testing helps to obtain a better understanding of the possibilities and limitations of each component and the system as a whole. In this case, it would be important to investigate the factors that affect the working of the system. Currently the system used for testing is used in production. In an environment specifically designed for the purpose of testing, one could make and test all necessary changes to the system without affecting the production environment.

7.4 Security

It becomes necessary in networked environments to secure the system from unauthorized access as an unwanted visitor can disrupt the activities of the system. Even read-only access may be dangerous as sensitive information about the internal structure can be derived from the exchanged messages. In these cases, it is often desirable to encrypt the messages that are sent between the components to avoid eavesdropping. Perhaps message encryption at application level can be used for the messages that are sent using the message queue (e.g., using *public-key cryptography*, where the Kafka producer can use the public key to encrypt the messages, whereas the Kafka consumer can decrypt the messages using the private key).

The current implementation of the Green Mind system allows all messages to be sent from all components. As future work, it would also be important to implement a more sophisticated access system (e.g., *ACL*) that does not only limit which messages can be sent by each component, but also features multiple users with manageable permissions that specify what operations are allowed to provide the system with an additional level of security against unwanted visitors.

7.5 Administrator panel

The independent configuration and maintenance of the components, sensors and actuators is possible. Administrators have to manually monitor the state of the components and configuration of these components is done locally through settings files. Although maintenance does not require recompiling it is by no means as easy as it could be.

As a first step it would be of help to have statistics for each component, sensor and actuator (e.g, *uptime*, *downtime*, or *cpu usage* for components) to determine their current status. As log files have proven useful in helping to maintain the components and to investigate problems, one area of future work is to combine their information with the statistics to provide easier means of access. However, only a small subset of all possible behaviors is currently represented in the log files. Extending the log files to include more behaviors will provide a wider variety of information for administrators to investigate.

A next step would be to add notifications, which requires monitoring and acting upon the reported statistics. For example, if a component, sensor or actuator is down an administrator is able to receive a notification to investigate the cause. In case of the components is perhaps also possible to remotely start, stop or restart each individual component. In the end the panel should be automated to the point that it is not always required to have physical access to the system and that downtime of a component, sensor or actuator is kept to a minimum.

Another area of interest is the more sophisticated access system that was described in the Section 7.4. The nature of such an access system would require a panel to manage users with manageable permissions as well. As such, combining the access system panel with the administrator panel may help the user by providing a single point of entry to all administrative tasks.

By using a web interface to access the administrator panel, it could provide access to nearly all users. In addition, a mobile client for platforms such as *Android*, *iOS* and *Windows Phone* could be of assistance too (e.g., for instant notifications to the administrators).

7.6 Extending rule support for controller

The rules for the controller provide the ability to control the connected sensors and actuators. Even though rules can be specified for a whole range of similar devices (e.g., lights, computers), it is possible that there are multiple similar rules due to personal preferences. Perhaps the rules should be designed in such a way that users can specify their own preferences for each rule. For example, by adding a generic rule for lights where each user or room can specify the minimum amount of light intensity before the associated lights are switched off. Another area for further exploration is the possibility of overriding a rule or device by the user (e.g., to keep a computer turned on during the weekend). Both the personal preferences for rules and the ability to override the rules can prove to be useful for the user acceptance rate of the system.

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Glossary

Acronym	Explanation
ACL	Access Control List
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
BMS	Building Management System
GUID	Globally Unique Identifier
HVAC	Heating, Ventilation, and Air Conditioning
JSON	JavaScript Object Notation
NFC	Near Field Communication
PIR	Passive InfraRed
RDF	Resource Description Framework
REST	Representational State Transfer
RFID	Radio Frequency Identification
SaaS	Software as a Service
SAGW	Sensor and Actuator GateWay
SMS	Sleep Management Server