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Improving Energy Efficiency of Residential Building Automation System Considering User contexts enriched by Smartphones

- German Use case -

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ABSTRACT

Harz University of Applied Sciences
Department of Automation and Informatics
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Master's Thesis

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The residential sector represents a big part of the energy consumption. In Europe, households represented 25% of the total energy consumption in 2014. Furthermore, the International Energy Agency in 2013 established a goal of 77% reduction of the carbon footprint when compared to 2050. One approach for saving energy is by introducing Building Automation Systems (BAS) which can reduce the residential carbon footprint by 38% in the German scenario. User context detection can help to improve the overall carbon savings from BASs, and smartphones can be used for user context detection. In this work, a smartphone was integrated to a BAS, in order to explore its benefits by increasing heating efficiency in residential BAS for one bedroom. Besides heating, lights, and some appliances in the house were also controlled by the use of smartphone sensors such as: GPS, infrared, light, accelerometer and gyroscope. The following user contexts were identified: user occupancy and activities as sleeping, awakening, and partying. In order to compare the energy efficiency of the current system, the heater response was simulated for four scenarios: fixed schedules, presence detection by motion sensor and exit button, absence of controllers and the ideal response. Preliminary results, show that the introduction of smartphones in BASs can increase energy efficiency from 14% to 50% when compared to other solutions.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

BAS	Building Automation System
EC	European Commission
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
NO	Normal Operation
LO	Lowered
RG	Research Goal
RQ	Research Question
WBCSD	World Business Council for Sustainable Development

1 INTRODUCTION

This research focuses on integrating a smartphone in a Building Automation System (BAS) by considering the user context identified through smartphone sensors. Actuators will change the conditions of the environment, and the purpose of integrating these concepts is to improve the energy efficiency of BASs.

In this chapter, it will be described the motivation and objectives of this work. Additionally, the contribution of the project regarding sustainability and building automation fields will be discussed. Finally, the organization of this thesis is explained.

1.1 Background

The residential sector represents great part of the energy consumption in a country. In Europe, households represented 25% of the total energy consumption in 2014 (EuroStat, 2016). Furthermore, the energy consumption in Europe has also increased by 29% from 1990 to 2014 (EuroStat, 2016). In Europe, space heating contributed for around 67% of the total energy consumption in residential buildings in 2012 (Odyssee-Mure, 2015). Fig. 1 shows the energy consumption by end-use for a diversity of European countries. In Germany, space heating corresponded to 75% of the households' energy consumption, appliances and lighting to 12%, water heating to 13% and cooking to 1%. Also, Germany was in the 11th position in the European ranking.

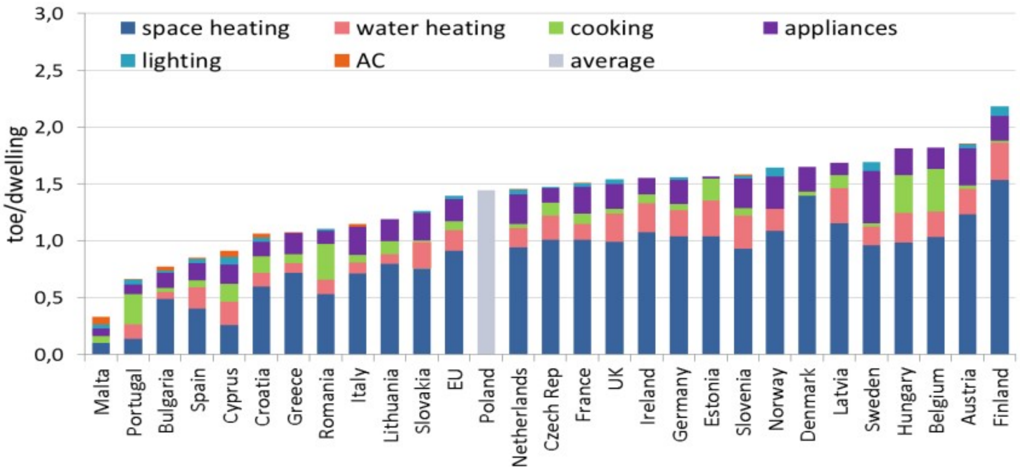

Fig. 1. Household energy consumption by end-use (Odyssee-Mure, 2015).

In order to lower the energy consumption, the International Energy Agency (IEA), which has 28 countries as members (including Germany), has a goal of reducing the carbon footprint by 77% compared to the 2050 baseline (IEA, 2013). Another initiative promoted by the European Commission (EC) in 2007 was the 2020 package which has the following goals (EC, 2007): 20% reduction in greenhouse gas emissions when compared to 1990, establish 20% of EU energy based on renewables and improvement of energy efficiency by 20%. As the residential sector stands for a large part of the carbon footprint, it is a potential target for improvements.

The World Business Council for Sustainable Development (WBCSD) showed in 2009 that it is possible to cut down the energy use in buildings dramatically by changing the user behavior (WBCSD, 2009). One approach for saving energy is by introducing BASs which can reduce up to 38% of the carbon footprint in the German residential building scenario, and for space heating specifically it can reduce up to 42% of the carbon footprint considering the same scenario (Sangogboye, 2015). In order to get these results with BASs, the user context is relevant because the usage of appliances, heater, etc. may vary from one user to another.

Smartphones can be introduced for improving the awareness of the system as the possibilities and availability of communication and sensors of mobile devices has been growing (Hoseini-

Tabatabaei, Gluhak, & Tafazolli, 2013). It is also assumed that the user carries a smartphone outside the house, so more information regarding the user context can be detected like the user's intention to arrive home. Therefore, building automation sensors cannot provide the same information as smartphones, and if they could, another device would be responsible for that, and the user would have to invest in the system buying extra sensors.

1.2 Goals

This work has the following research goals (RGs):

- **RG1** (main Research Goal): Explore the benefits of the smartphone solution when integrated in the BAS regarding energy efficiency (thermal and electrical).
    - This is the main Research Goal, and it reflects the thesis title. Thermal energy and electrical energy consumption benefits are explored.
- **RG2**: Formulate a computational model in order to calculate heater performance and errors.
    - For comparing different scenarios, this computational model will be followed. Also, this is only performed for the heater as the focus of this research is with the heater response. Each scenario can have performance and errors generated through the day, and this is identified by comparing scenario with an ideal scenario which shows the correct heating response.
- **RG3**: Recognize user contexts through the integration of a smartphone to a BAS
    - The user context can be identified by using smartphone sensors, and specific algorithms.
- **RG4**: Use the detected contexts to optimize the BAS
    - User contexts are identified for sending response to actuators in order to save energy and maintain comfort for the user.
- **RG5**: Compare the smartphone vs. simulated scenarios solutions.
    - The smartphone approach is also compared to other relevant scenarios in order to present the benefits of the smartphone solution regarding the user behavior.
- **RG6**: Give feedback information for the user regarding all scenarios.

- By comparing showing each scenario efficiency the user can configure the BAS based on the scenarios response, so the system best fit the user needs.

1.3 Delimitations

This section describes the three delimitations topics which were considered on this thesis: buildings, energy consumption and use case scenarios.

Buildings can be classified in nonresidential and residential. In Europe, residential buildings represent 60% of the total residential energy consumption depending on the location (Odyssee-Mure, 2015). For this reason, this thesis only focuses on residential BAS investigation. Additionally, the German use case was also analyzed based on Sangogboye (2015).

As heating corresponds to 67% of energy consumption in Europe (Odyssee-Mure, 2015), the main focus of this thesis is comparing the heater response of the smartphone approach regarding three other scenarios which are also based on Siemens report (Siemens, 2012): absence of controller, fixed schedules and presence detection (through motion sensor, and exit button). Additionally, thermal energy management is explored by controlling a radiator.

Appliances, which use electrical energy, correspond to around 11% of the energy consumption in Germany, and it is suggested that some home appliances (vacuum cleaners, washing machine, etc.) cannot be further optimized as the energy consumption with or without BAS are the same (Sangogboye, 2015). Lights correspond to around 1% of energy consumption in households in Germany (Odyssee-Mure, 2015). For these reasons, lights and appliances are not investigated in detail, but they were integrated in the smartphone approach development, and compared from other scenarios through discussions.

Finally, Sangogboye (2015) considered the German use case scenario involving only a person living alone, and the same approach is taken in this work. This situation corresponds to 31.7% of household in Europe (EuroStat, 2013). This thesis also analyses the heating, appliances and lighting controllers in a bedroom where the user also sleeps. Additionally, this use case will be explored by real reproduction of the user actions in this bedroom.

1.4 Research Questions

The following list describes the Research Questions (RQs) of this work:

- **RQ1** (main Research Question): How energy efficiency is affected when the user context and introduction of smartphones are considered for German residential BAS?
- **RQ2**: What methodology can be used in order to qualify the heating response?
- **RQ3**: Which user's contexts are more relevant to be identified in order to control heating, lighting and appliances usage?
- **RQ4**: Which sensors and algorithms can be used in order to identify more precisely the user context when smartphones are integrated?
- **RQ5**: Which scenarios are more relevant in order to compare energy efficiency in BASs specifically when the user context is taken in account?

1.5 Traceability Research Questions and Research Goals

Table 1 shows the traceability between Research Questions and Goals. All research questions support the investigation of at least one research goal.

Table 1. Research Questions and Goals traceability.

Research Questions	Research Goals
RQ1	**RG1** , **RG5**, **RG6**
RQ2	**RG2**, **RG5**
RQ3	**RG3**
RQ4	**RG4**
RQ5	**RG1**

1.6 Research Method

For **RQ1**, a BAS report from Siemens (2012) is adapted and integrated to smartphones and user contexts. This report is based on the standard EN15232 (Standard, 2012). **RQ2** is explored by comparing the smartphone based approach and three other simulated scenarios to an ideal scenario. The comparing method is based on the Siemens report previously mentioned, and it is based on comparing heater responses during the day with an ideal scenario which is also simulated and based on the same report. **RQ3** and **RQ4** are explored based on the literature review by identifying the most relevant contexts, sensors and algorithms. Finally, **RQ5** is based on Siemens (2012) and Sangogboye (2015) works for identifying the most relevant scenarios in the German context.

For analyzing the solution, two scenarios are investigated: one where the user follows explicitly a German Use Case described by Sangogboye (2015), and another where the user delays his/her actions when compared to the proposed schedule.

1.7 Thesis Contributions

The contributions of this work are related to the BAS and the Sustainability fields. For the BAS field, the contribution is based on the incorporation of smartphones in order to increase the energy efficiency of the system. Additionally, this work contributes by creating a comparison method between different scenarios and heating responses based on the user context in order to support different systems being analyzed regarding energy savings.

For the Sustainability field, this project contributes for the pillars of sustainability: Economy, Society and Environment. For the Economic pillar, the lower energy consumption of a building system can be converted into a faster ROI and reduce costs for its owner as shown by Sangogboye (2015), as the system may provide better energy management. For the Society pillar, eco-feedback is promoted by showing to the user which BAS configuration is more relevant depending on the user habits, and strictness in comparison to fixed schedules and other scenarios. For the Environment, the user will save thermal and electrical energy, therefore, reducing CO_2 emission.

1.8 Structure of the Thesis

This thesis is structured in six chapters. The first one presents the introduction, motivation, goals and research questions. The second one is the literature review which introduces the background, technologies and related works in different field which are relevant for this work. Chapter three describes the methods used for implementation of the tool by presenting the German use case, the method for the heating comparison between scenarios, the BAS scenarios, and the developed platform. Chapter four describes the results based on two use cases: when the user has a strict and unpredictable behavior. Finally, chapter five presents the results analysis, and chapter six the conclusion.

2 LITERATURE REVIEW

This chapter is divided in three sections, Background, Technologies and Related Works. The first one presents fundamentals, the second one presents a diversity of technologies which are related to the solution implementation and the third one investigates other papers in order to explore the Research Goals and Questions described in 1.2 and 1.4, respectively.

2.1 Background

The background of this thesis involves Building Automations Systems and the User Context representations in the BAS field.

2.1.1 Building Automations Systems

BAS is an automatic and centralized control of appliances and resources inside any kind of building (houses, hospitals, companies, etc.). It is possible to use a diversity of sensors and controllers. Sensors are used to gather information from the environment as temperature, motion, etc., and controllers or actuators are used to change the environment as heating, lighting, power supply, etc.

Sensors and actuators can be based on many different protocols, e.g., FS-20, HomeMatic, Intertechno, EnOcean, Zigbee (Vesternet, 2012). They have different specifications, and also applications in which they are more relevant (Goswami, 2015). Some relevant Germany-originated protocols are compared in section 2.2.1.

Centralization control usually occurs through a server which enables user control and awareness so the user can see outputs from sensors and have the possibility to control actuators manually if the application installed in the server enables it. In this case, the user can be aware of what is occurring in the building.

A smarter BAS would automatically control actuators based on sensors input data by creating contexts which create more abstract information regarding the behavior of the user. The automations and contexts detection algorithms could also be installed in the server.

The benefits of BAS are energy saving, greater comfort and security for the owners (Merz, Hansemann, & Hübner, 2009). Many devices can be applied to guarantee diverse benefits, for instance higher security can be provided by automatic lock or identity recognition when the user arrive.

It is also relevant to differ commercial and residential BAS. In the commercial BAS, it can be more challenging to understand and abstract contexts as there are many users involved. Heating, ventilation and air conditioning (HVAC) has also interesting advantages for commercial buildings and owners as studies have affirmed that workers have greater performance and productivity if they are in good temperature conditions (Merz, Hansemann, & Hübner, 2009), but this would be applied for residential BAS and residents as well. Another point is that the installation of devices in the commercial BAS have to provide flexibility, as the layout of the room in commercial areas can be changed to support more employees for instance.

On the other hand, in the residential BAS it is easier to gather and understand contexts, and the system can be can be less flexible. This occurs because usually there are less users involved.

2.1.2 User Context in Building Automation Systems

One definition of the user context in BASs involves the user behavior and his interaction with the building which are illustrated in Fig. 2. The user behavior is an interaction described by 5W questions (what, when, who, why where) and 1 H (how). So, it is possible to identify a specific user behavior for a determined time, place, person, etc. The building context relates a user to the building itself, as the place where a person is located, and his/her interaction with objects of the house, environment temperature at the moment, etc.

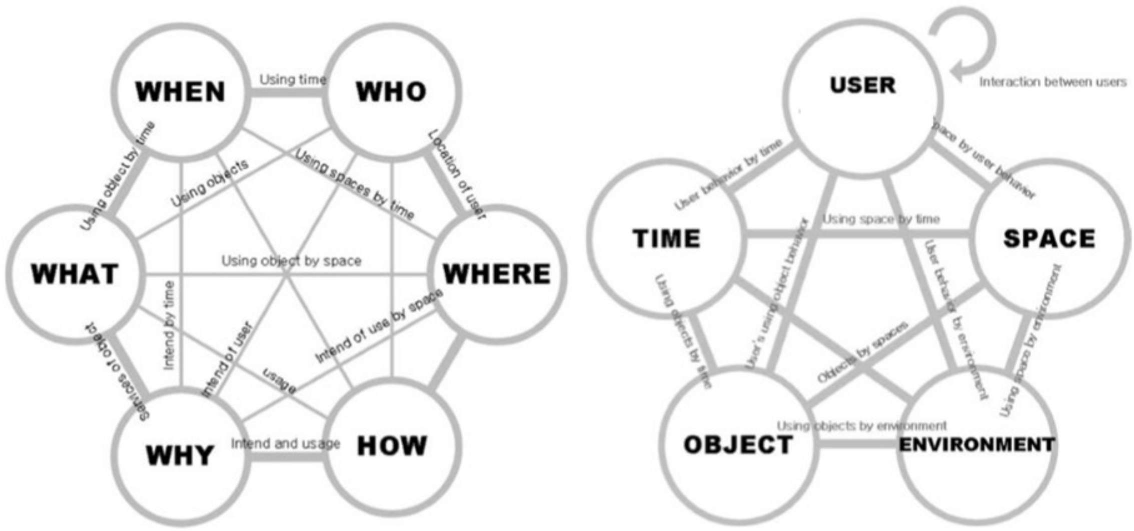

Fig. 2. Diagrams of the user behavior and building context (Ha, Jung, & Oh, 2006).

It is also possible to observe that the user behavior and the building context can be related to each other as the user behavior affects the building context. For example, in building context the user interaction with an object, in a specific time and place can be related to who (the user), what (an object), when (specific time) and where (specific place) questions.

In order to understand the user context, an inference system is needed, so that the data collected from sensors is converted in a more abstract information which is the user context. Logical inference is normally used in order to detect real time user context, and Bayesian inference can be used to predict the user context (Nguyen & Aiello, 2013). Also, in real time context detection for cameras, RFID and ultrasonic sensors the usage of Bayesian is more common (Nguyen & Aiello, 2013).

An example of logical inference rule for the user context of going out to work is illustrated in Fig. 3 where user washes up, dress up, locks door (probably from his bedroom), closes window from living room and veranda. After that the user locks the two front doors, and checks if the doors are locked.

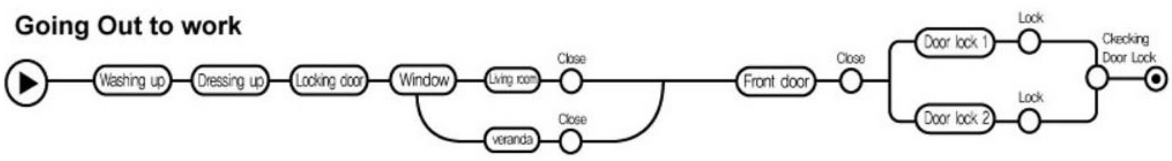

Fig. 3. Identification of going out to work context (Ha, Jung, & Oh, 2006).

This user context can be identified by motion sensors near the faucet to check when the user is washing up, movement sensors in the closet, door and window sensors. Finally, an algorithm based on rules can be developed in order to identify this specific context.

Obviously, this user context is detailed with many steps which could be suppressed to simplify the system. For example, this same context could be when doors are locked and there are no movements in the place for 10 minutes after that. If smartphones are integrated to the system GPS coordinates of the user could be tracked for location detection, simplifying even more the solution.

In Fig. 3 it is possible to observe that each box describes a user action could be described by user behavior and building context in Fig. 2. The sequence of all these actions result in the user context.

As an example, a similar user context description is used by Kashif, et al. (2013) where user contexts are gathered by questionnaires based on intervals, name of the user, activities and objects interaction.

2.2 Technologies

This section introduces available technologies relevant for this thesis as: Home Automation Sensors and Actuators Protocols, Smartphone Sensors and Home Automation Platforms

2.2.1 Home Automation Sensors and Actuators Protocols

Sensors and actuators can have different protocols to communicate with the BAS system. Protocols can also rely on wired or wireless communication. In this section, the wireless protocols HomeMatic[1], EnOcean[2], Intertechno[3] and FS20[4] are analyzed briefly. Table 2 summarizes features claimed by vendors of relevant wireless protocols which have devices in German retailer shops. The table is organized by their frequency, reachability, communication type, number of products, and further advantages promoted by the owners. Other relevant information is that all these protocols are proprietary, and it was also noticed that the amount of HomeMatic devices is higher in retailer shops.

Table 2. Comparison between relevant home automation protocols and devices in Germany.

Feature	HomeMatic	EnOcean	InterTechno	FS20
Frequency (wireless)	868MHz	868MHz(Europe)	433Mhz	868Mhz
Reachability	100m (outdoors)	30m indoors, 100m outdoors	30m (indoors)	100m (outdoors)
#Products	Around 80	Up to 1500	Up to 40	At least 100
Further advantages	noise immunity, security and low energy consumption	The protocol relies on the ISO/IEC 14543-3-1X standard	Lower frequency offers better penetration of the signal through walls and doors	Fail-safe

2.2.2 Smartphone Sensors

Smartphone sensors can be categorized in three groups inertial, positioning and ambient sensors (Hoseini-Tabatabaei, Gluhak, & Tafazolli, 2013). Table 3 describes these categories, the sensors involved, and the information collected by each sensor.

[1] http://www.homematic.com/
[2] https://www.enocean.com/en/
[3] http://intertechno.at/
[4] http://fhz4linux.info/

Table 3. Smartphone Sensors

Category	Description	List of sensors	Sensor information
Inertial	Measures physical motion	Accelerometers	Applied acceleration
		Gyroscopes	Inertial angulation rotation
Positioning	Measures user location and presence	Bluetooth	Presence detection of other Bluetooth devices close to the user
		GPS	Geolocation and time information
Ambient sensors	Measures surroundings	Magnetometer	Magnitude of the magnetic field
		Microphone	Sound

2.2.3 Home Automation Platforms

Home automation platforms are frameworks which provide devices and functions integration and accessibility in the system. It is possible to integrate sensors, actuators and for more flexible solutions, in which the user is also partially a developer, algorithms implementation for home automation.

The server is installed in a desktop or a microcontroller as Raspberry PI[5] which offers credit-card size microcontrollers with many possible I/O interfaces, and the latest model costs 35$ and the cheapest one 5$. Microcontrollers are usually used as they spend less energy than desktops, and the user can leave it turned on 24/7.

For server accessibility, the interaction of the user with the system is usually through http, and through the interface it is possible to check the state of sensors and change response of actuators, connected to the platform. Each platform is based on a program language, also some platforms provide some specific languages for automation so that the user does not have to be fluent in programming.

[5] https://www.raspberrypi.org/

Additionally, platforms work with specific devices and protocols listed by the organizations. Table 4 shows the comparison between three home automation platforms explored in this thesis FHEM[6], OpenHab[7] and Home Assistant[8]. These platforms support all protocols described in section 2.2.1. Pairing with devices can be performed by the platform itself (as it works in FHEM) or by using 3rd party software. Finally, the three platforms support MQTT[9] which can be used for smartphone and server communication through Internet.

Table 4. Home Automation Platforms comparison.

Feature	FHEM	OpenHab	Home Assistant
Server programming language	Perl	Java	Python
Automation programming language	Specific rule language and commands	Java-like language	Python-like language and Python[10].
Further features	Supports logging event, charts, scheduled commands and event driven communication between modules	Logging through files and Cloud	Easily integration of Google Calendar, Google Maps Distance Matrix, and graphical history.
3rd party software for Pairing	Not required	Required	Required
Tool Community Updates	SVN and forum	GitHub and forum	GitHub and forum
Documentation	Command lists, devices supported, tutorials and helper modules		
Protocols	Support all protocols described in section 2.2.1, and more.		

[6] https://fhem.de/
[7] https://www.openhab.org/
[8] https://home-assistant.io/
[9] http://mqtt.org/
[10] https://home-assistant.io/blog/2016/08/16/we-have-apps-now/

Community and documentation language	Mostly in German	English	English
License	GPL’d	Eclipse Public License V1.0	Apache V2.0

The interface of FHEM is shown in Fig. 4, although it is possible to change this view by using a different HTML code, or by downloading different add-ons on the website.

Fig. 4. FHEM web and Smartphone applications.

Fig. 5 and 6, show the OpenHab user interface in Android and the web applications respectively.

Fig. 5. OpenHab Android classic UI.

Fig. 6. OpenHab web classic UI.

Fig. 7 shows the Home Assistant user interface in Android and the web applications respectively.

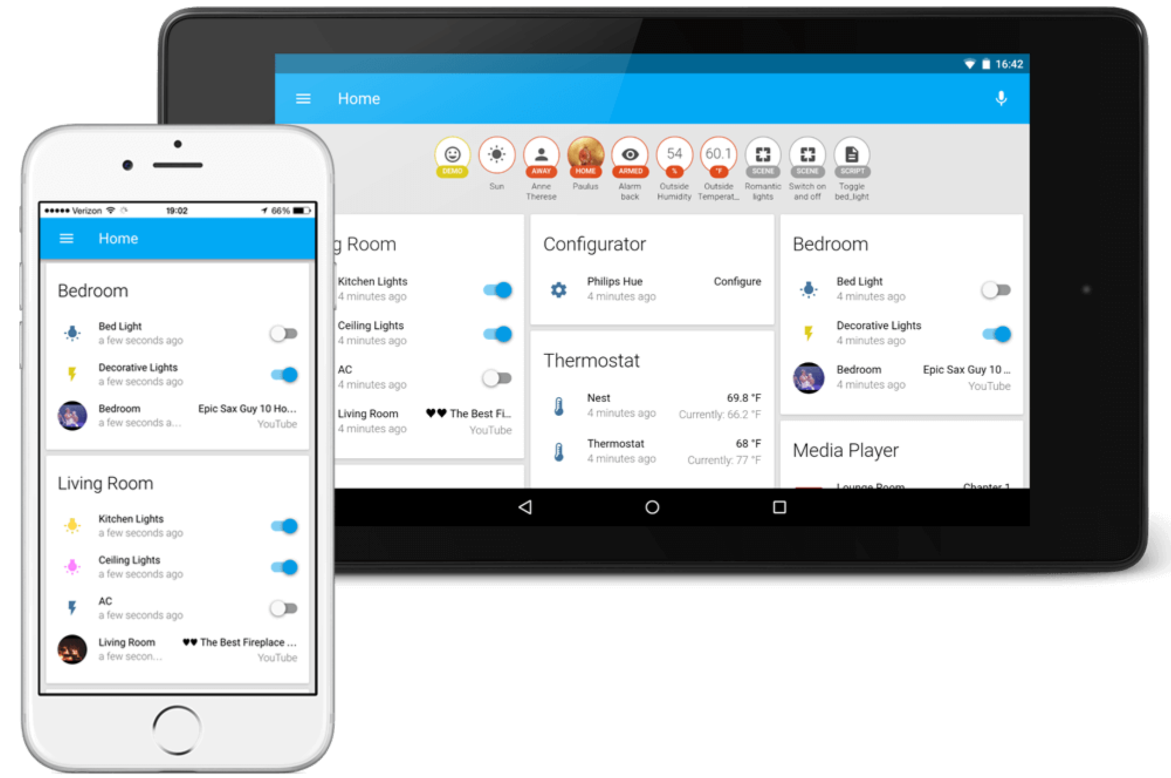

Fig. 7. Home Assistant mobile and web application.

2.3 Related Work

Related work is divided in five topics: “User Behavior Influence in Building Energy Consumption”, “User Context Detection in Building Automation Systems”, “User Context and Smartphones” and “Mobile Devices in Building Automation Systems” and “Building Automation Energy Efficiency”. The last one describes the most important details followed for the implementation of the current work. It was also noticed a lack of papers exploring the benefits of Smartphones integrated in BAS when User Context are considered.

2.3.1 User Behavior Influence in Buildings Energy Consumption

Two types of user behavior influencing energy consumption were analyzed: how user behavior can influence the energy consumption in buildings, and how user behavior can be changed through energy consumption feedback information. The purpose of this section is to explain the relevance of the **RG6** regarding eco-feedback for the user and energy consumption. Three works are investigated for the first type, and five other papers for the second one.

Grinewitschus, et al. (2013) measured temperature, CO2 concentration, and humidity for 80 apartments during two weeks. With this information, it was possible to recognize the user behavior regarding ventilation of the place by, for example, inferring the user is opening or closing windows. Buildings which had similar structures were compared, and it was found out that some of them had higher energy consumption due to ventilation of the place for several hours per day. On the other hand, apartments ventilated for shorter periods had lower energy consumption. Therefore, user's behavior regarding ventilation affected the energy consumed in the use cases analyzed.

Masoso & Grobler (2010) carried a study in Botswana and South Africa showing the influence of the user occupancy in five commercial buildings. Results show that more energy was used in non-working hours (56%) than working hours (44%) due to the lack of controls and discipline, as by leaving equipment turned on even after work hours. For that purpose, the consumption of HVAC, appliances and lighting was measured and analyzed for different periods in buildings ranging from one month to a year.

These papers show examples of the user behavior influencing energy consumption of buildings, one method to change the user behavior and lower energy consumption is by promoting social greening and awareness through feedback information.

Zhao, et al. (2017) analyzed 300 residential units, and education/training on building systems, which is related to social greening, was one of the behaviors identified affecting energy consumption directly

Regarding feedback representation forms, Jain, et al. (2013) investigated that the type of information displayed to users may have better benefits as energy savings achieved 10% for a specific group in which energy was converted to an environmental externality unit (number of trees required to offset CO_2 emissions). Although, Froehlich, et al. (2010) argued that further analysis has to be accomplished in order to confirm which representations give best results for saving energy.

Fischer (2008) reviewed 21 papers in order to explore the feedback energy consumption impact on users. Results from papers analyzed in the survey show that energy savings achieved 1.1% up to 20%, and in a few papers no savings were achieved. The paper also analyses the best type of feedbacks in order to give best results, and it concludes they should be based on the actual energy consumption in a daily basis through a long period of time in an appealing and clear way by interactive and computerized tools. Additionally, they can involve historical and normative comparisons.

On the other hand, in McKerracher & Torriti (2013), 33 papers were analyzed, and it is shown that through eco-feedback in home displays energy savings achieved only 3-5%. This difference occurred compared from the precious study because more recent papers were analyzed.

These papers show that eco-feedback can be an option for changing the user behavior and improving energy consumption, and it justifies the relevance of **RG6** in the project. Therefore, the current work incorporates this principle in order to show the user the relevance regarding his/her behavior and different scenarios in which the heating can be controlled. For that purpose, eco-feedback can be performed by showing charts containing statistics so that the user can compare solutions in a daily basis through a computational method as recommended by Fischer (2008).

2.3.2 User Context Detection in Building Automation

In this section, different methods and their relevance are explored in order to apply user context detection in building automation towards saving energy consumption and improving user comfort. The intention is to explore **RQ3**, so seven papers were analyzed.

Cano, et al. (2013) proposed a system which deals with energy efficiency, comfort services, environmental monitoring and security for building automation. The main purpose of the paper was to control HVAC and lighting of an office. In order to achieve that, an automation platform called CityExplorer gathers information from sensors and actuators, monitors them by identifying anomalies, and takes actions by dealing with key efficiency parameters as saving energy or water. The developed system uses the standard EN15251 which specifies the criteria for energy systems in buildings and evaluates the indoor environment. Additionally, for the comfort management, it was used models for predicting the comfort response of occupants in building. The system also auto adapts its operation through user interaction. Results showed that about 20% of the energy consumption could be saved.

Mehrabi, et al. (2014) used three techniques to identify user context in BAS: role-based flow charts, adaptive home automation system, and thermal modeling of the area for energy conservation. Role-based flow charts were developed for each area and device of the house. Adaptive home automation system proposes that the system adapts itself to the needs of the user. Thermal modeling of the area for energy conservation considers modeling the response of the HVAC system, so that it is possible to find the pattern for the control signal by understanding the valve position and radiator response.

In the described above adaptation of the system and prediction of the user behavior was implemented. Although, one assumption of this work is that through the use of smartphones more information regarding the user behavior will be available for the BAS and the user presence could be detected in order to control the heater response. Therefore, prediction and adaptation could not be necessary for simpler scenarios as residential building because more information regarding the user activity is available for the BAS. Table 5 summarizes methods, controllers and results from three papers indicating that user presence is an important factor for energy saving reaching up to 30% energy savings. After that two other surveys were also analyzed.

Table 5. Occupancy detection relevance for energy saving.

Paper reference	Occupancy Detection Methods	Controllers	Results
Lu, et al. (2010)	Motion and door sensors	HVAC response	8 residences analyzed where up to 3 people living together. 28% energy savings

Gao & Whitehouse (2009)	Motion and magnetic reeds on doors	HVAC scheduling response	Energy savings up to 15% when compared to the default schedule by EnergyStar.
Dong & Andrews (2009)	State transitions of sensors for acoustics, illumination, motion, CO_2, temperature and relative humidity	HVAC response	30% simulated through EnergyPlus

Nguyen & Aiello (2013) performed a survey focusing on registering the most important user activities in order to save energy and improve the user comfort. For that purpose, the survey explored HVAC, lighting and plug loads. Table 6 shows the potential savings and main approaches used for HVAC, lighting and appliances. Most of the approaches involved occupancy detection. Also, it was described that logical inference from sensors is more common to be used for real time occupancy recognition when simple sensors are considered.

Table 6. Potential savings for respective devices and approaches (Nguyen & Aiello, 2013).

Device	Energy saving potential	Approach
HVAC	Up to 40%	real-time occupancy
Lights	Up to 40%	real-time occupancy with user preference
Appliances	Not evaluated	real-time occupancy

Mirakhorli & Dong (2016) analyzed many papers regarding their approaches for occupancy based model predictive control. Most studies analyzed used PIR, Camera, door sensors, phone, wi-fi and GPS in order to detect user presence and number of users.

This section contributed to explore **RQ3** by showing that user occupancy is relevant for BAS in order to save energy. Papers showed that occupancy detection can be used for heating, lighting and appliances control, therefore, when smartphones are introduced different sensors can be used for detecting it. Furthermore, logical inference can be used for occupancy recognition, this will also be taken in consideration for the algorithms chosen for user context recognition

2.3.3 User Context and Smartphones

In this section, sensors and algorithms for user context detection are analyzed. The intention is to explore **RQ4**. For this purpose, Table 7 compares four papers by sensors, user contexts detected, algorithms and results. As shown, accelerometers are mainly used for user's position and activity recognition, and GPS for occupancy. Afterwards, two surveys were also analyzed.

Table 7. Sensors used for user context detection

Paper Reference	Sensors	User Context	Algorithms	Recognition Rate
Baek & Yun (2010)	Accelerometer	user's posture: sitting, walking and standing	Butterworth low-pass filter	99.7%
Chen & Shen (2017)	Accelerometer	walking, jogging and stairs crossing were detected through the use of accelerometers	Nearest neighbors, random forests and support vector machines	96%
Khalifa (2013)	Accelerometer	standing: on the floor, on escalator and in a lift	multilayer perceptron	94%
Mafrur, et al. (2015)	GPS, accelerometer and magnetometer	Occupancy: indoor and outdoor positions. Activities: walking, running, standing, sitting.	SVM	92%

Yürür, et al. (2016) performed a survey involving papers between 1991-2014 and considering context-awareness for mobile devices is performed. Besides reviewing papers, the survey also summarized definitions from other papers regarding awareness in the mobile devices field. Table 8 summarizes the most important findings in this paper related to this thesis as the user context definition for smartphones, and description of applications approaches and results.

Table 8. Relevant user context definitions and applications (Yürür, et al., 2016)

Topic	Findings
Contextual Information	Defined as an abstraction of an entity situation, e.g. user location.
Context Representation	Divided hierarchically: • low-level (sensed): physical, virtual and logical sensors; • high-level (inferred): device, user, physical and temporal contexts; • situational relationships (presumed): user state.
Context Modeling	Possible modeling schemes: key value, mark-up scheme, graphical, object oriented, logic based and ontology based.
Context Inference	Definition divided in: • Feature selections: time domain, frequency, etc. • Classification algorithm: Decision tree, Bayesian Network, Fuzzy, Multilayer Neural Networks, etc.
Applications Summary	For human activity recognition, 11 papers were analyzed using smartphones. For that purpose, accelerometer, GPS, etc. were used in order to identify a variety of activities related to posture and movement. Outdoors location and transportation were identified through the use of GPS.

Hoseini-Tabatabaei, et al. (2013) reviewed papers which used smartphones in order to determine the user context which were acquired by opportunistic sensing. The paper described sensors, algorithms for context recognition, accuracies for activity recognition and goals of each studied work. User's location recognition was performed by using GPS, Wi-Fi and Bluetooth in some works which have used a combination of thresholds (as logical inference) and achieved 90% accuracy for that purpose.

The papers analyzed show that the accelerometer is relevant for user activities and posture detection. Also, for user location and transportation detection, GPS seems to be the most relevant. Although, it was not identified papers detecting user sleeping/waking up state. Logical inference through thresholds for user context detection is mentioned again in this section, and it will be taken in consideration for the tool development. The definitions of context representation hierarchically and user context modelling also enlighten ways to represent contexts in smartphones for the approach in this work. This section contributed to explore **RQ4**.

2.3.4 Mobile device applications in Building Automation Systems

Some platforms were developed in order to incorporate mobile devices in BASs. The purpose of this section is to analyze the options for implementation **RG2**. It was also noticed a gap in further studies analyzing the benefits of the smartphone integration in BAS.

Table 9 summarizes platforms which integrated smartphones in BASs, and it is possible to notice that four platforms concerned only to enable accessibility (sending direct commands to appliances and checking the response from sensors) through smartphones, and only one proposed an integrated system concerning context awareness applications. In section 2.2.1, it is also shown that internet is mostly used for integration of smartphones in BAS for accessibility purposes, and some platforms do not have specific Android/iOS so the browser is used for that purpose.

Table 9. Mobile Devices Platforms integrated to BAS

Papers	Features
Dickey, et al. (2012)	Enable accessibility through internet
Doukas (2013)	Platform which handles smartphone sensors, data processing, context-awareness recognition and communication with external resources.

Olteanu, et al. (2013)	Enable accessibility through ZigBee protocol.
Mandula, et al. (2015)	Enable accessibility through Bluetooth or and internet communication
Rojas-Rodríguez, et al. (2015)	Enable accessibility through Bluetooth

For sending information from the smartphone sensors to the server there are two possibilities. The first one is by using existing applications which send specific data through MQTT as OwnTracks[11] to the server. The second one is to develop an application which can handle anything the developer wants to integrate. For complex systems which have to perform inference in the smartphone applications an application has to be developed as proposed by Doukas (2013).

2.3.5 Building Automation Energy Efficiency

This section explores the research questions **RQ2**, **RQ3** and **RQ5** by presenting a report from Siemens (2012): "Building Automation - Impact on Energy Efficiency" which describes an approach to measure the relative performance of a BAS compared to another. They also presented some brief results on some typical baseline systems' performance. Their approach is based on a model driven methodology to save energy in building automation, and it applies the standard EN15232: "Energy performance of buildings - Impact of Building Automation, Control and Building Management" (Standard, 2012) which specifies the following methods to evaluate BAS and building management:

- A structured list of controls and functions which have impact in the energy performance of buildings;
- Methods to define the minimum requirements for controlling and managing buildings of different complexities (the report give extra recommendations);
- Methods to assess the BAS functions (mentioned in the first bullet) on building energy performance. It also provides the impact of these functions which can be used for calculations in the energy performance rating and indicators from other standards;

[11] http://owntracks.org/

- A simplified method to get estimations of the functions impact for typical buildings.

By applying functions, a system can be categorized in different classes regarding energy efficiency: D, B, C, A. Fig. 8. defines each one of the efficiency classes, and it shows that Class A is the most sustainable while Class D has no monitoring neither energy savings gains.

Class	Energy efficiency
A	Corresponds to high energy performance BACS and TBM • Networked room automation with automatic demand control • Scheduled maintenance • Energy monitoring • Sustainable energy optimization
B	Corresponds to advanced BACS and some specific TBM functions • Networked room automation without automatic demand control • Energy monitoring
C	Corresponds to standard BACS • Networked building automation of primary plants • No electronic room automation, thermostatic valves for radiators • No energy monitoring
D	Corresponds to non-energy efficient BACS. Buildings with such systems shall be retrofitted. New buildings shall not be equipped with such systems • Without networked building automation functions • No electronic room automation • No energy monitoring

Fig. 8. Classification and levels for BAS (Siemens, 2012).

The report contains functions for a diversity of controls: HVAC, hot water supply, cooling, lighting, blind and technical home and building management. Siemens has incorporated to the standard functions with their recommendations, and displayed the results in different tables. One example heating control function is shown in Fig. 9.

	HEATING CONTROL	Reason for energy savings
	The control system is installed at the emitter or room level, for case 1 one system can control several rooms	
0	No automatic control of the room temperature	The highest supply output is continuously delivered to the heat emitters resulting in the supply of unnecessary thermal energy under part load conditions.
1	Central automatic control There is only central automatic control acting either on the distribution or on the generation. This can be achieved for example by an outside temperature controller conforming to EN 12098-1 or EN 12098-3.	Supply output depending on the outside temperature for example (corresponding to the probable heat demand of the consumers). Energy losses under part load conditions are reduced, but no advantage can be taken of individual heat gains in the rooms.
2	Individual room control By thermostatic valves or electronic controller	Supply output based on room temperature (= controlled variable). It considers heat sources in the room as well (heat from solar radition, people, animals, technical equipment). The room can be kept comfortable with less energy. Comment: Electronic control equipments ensures higher energy efficiency than thermostatic valves (higher control accuracy, coordinated manipulated variable acts on all valves in the room).
3	Individual room control with communication Between controllers and BACS (e.g. scheduler)	Same reason as above. In addition central... • schedulers make it possible to reduce output during non-occupancy, • operating and monitoring functions further optimize plant operation.
4	Individual room control with communication and presence control Between controllers and BACS; Demand/Presence control performed by occupancy	Same reason as above. In addition: • Effective occupancy control results in additional energy savings in the room under part load conditions. • Demand-controlled energy provision (production of energy) results in minimum losses in provision and distribution.

Fig. 9. EN15232 functions and Siemens recommendations for energy efficiency regarding Emission Heating Control (Siemens, 2012).

In Fig. 9, the white blocks show the EN15232 standard function content, and in gray there are the Siemens extra recommendations and supplementary information regarding these functions. Besides the column "Reasons for energy savings", Siemens' report also gives extra recommendations and interpretation regarding the implementations of these functions.

Finally, it is possible to map functions which have to be followed in order to achieve a determined efficiency class. Fig. 10 illustrates such mapping. For Class A product, the approach has to have an individual room control with communications and presence control for residential and non-residential BAS.

			Definition of classes							
			Residential				Non residential			
			D	C	B	A	D	C	B	A
AUTOMATIC CONTROL										
1	HEATING CONTROL									
1.1	Emission control									
		The control system is installed at the emitter or room level, for case 1 one system can control several rooms								
	0	No automatic control								
	1	Central automatic control								
	2	Individual room control								
	3	Individual room control with communication								
	4	Individual room control with communication and presence control								

Fig. 10. Mapping of functions and energy efficiency classes, for the EN15232 functions (Siemens, 2012).

Fig. 11 illustrates a comparison between classes A, B, C and D heating and cooling controllers' response in an office in relation to the user's occupancy, and it is possible to observe that Class D has no automation for setting temperature for heater and cooler. On the other hand, Class C has specific set points when the user is occupying the place, and Class B has a better response than Class C because both heating and cooling set points are closer to the user's occupancy, therefore, less energy is consumed. Class A applies adaptive set points in the cooling or demand control air-flow, so it performs better than the other classes.

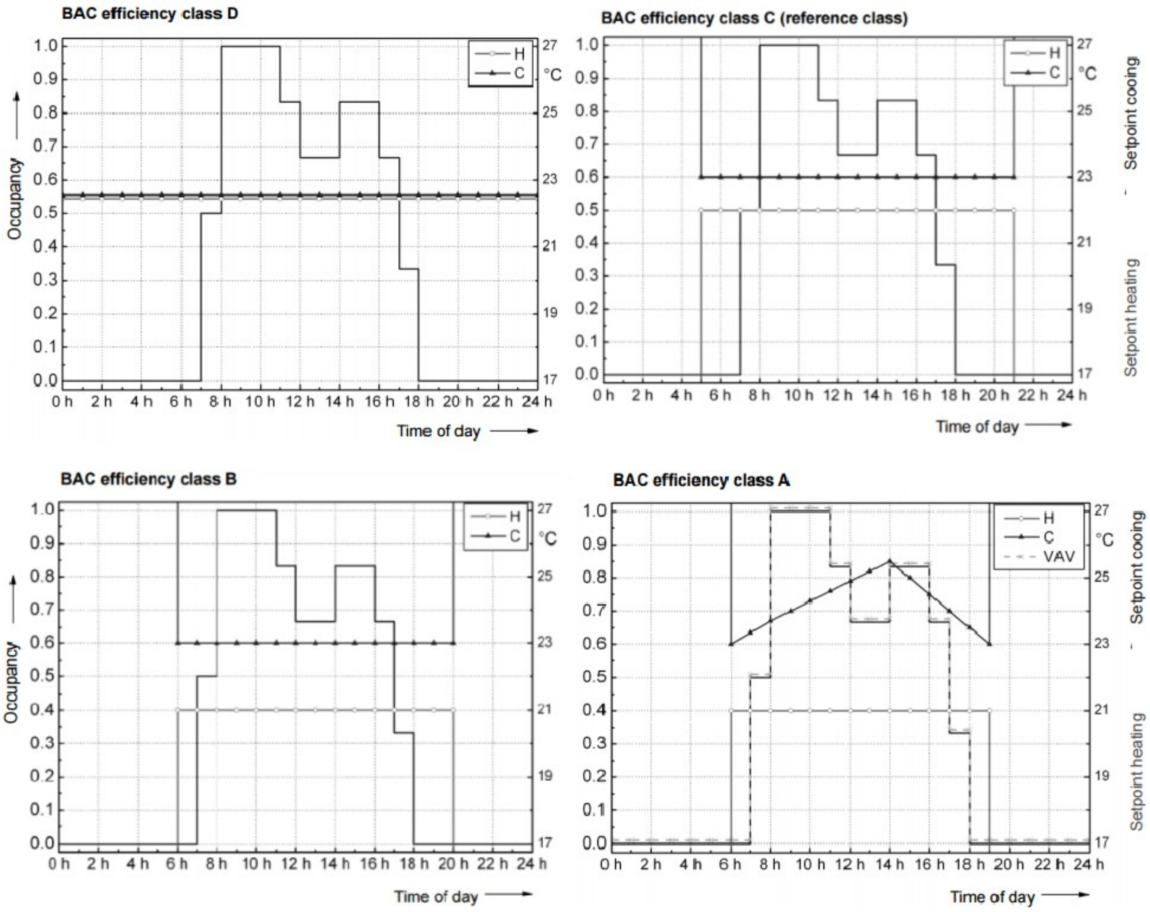

Fig. 11. Classes for cooling and heating operations based on user presence in a building office. H represents heating and C cooling operations (Siemens, 2012).

Table 10 shows the functions for heating, lighting and technical BAS management which should be followed in order to implement a system for determined class. It is noticeable that Classes A and B have integrate more automated functions, while in classes C and D many functions are operated manually.

Table 10. Functions and implementations from the Siemens report. Where 1.1 and 1.5 correspond to heating control, 5.1 and 5.2 to lighting control, 7.1 and 7.2 to Technical BAS management (Siemens, 2012).

Function	Class D	Class C	Class B	Class A
1.1 Emission control	Manual	Individual room control	Class C + communication through schedules	Class B + presence control

1.5 Intermittent control of emission and distribution	Manual	Auto. control + schedule	Auto. control + optimum start/stop	Auto. control + demand evaluation
5.1 Occupancy Control	Manual on/off	Manual on/off	Class C + sweeping extinction signal	Auto. detection
5.2 Daylight Control	Manual	Manual	Manual	Auto.
7.1 Fault detection + diagnosis	No	No	Yes	Yes
7.2 Reporting energy use + improvement possibility	No	No	Yes	Yes

Table 11 show results regarding thermal and electrical efficiency when classes are compared, and it is possible to observe that Class A when compared to Class D can save 35% and 17% of thermal and electrical energy.

Table 11 BAS thermal and electrical efficiency factors for residential buildings and classes (Siemens, 2012).

Class Name	Thermal Efficiency	Electrical Efficiency
D – Non-Energy Efficient	1.1	1.08
C – Standard	1	1
B – Advanced Energy Efficiency	0.88	0.93
A – High Energy Efficiency	0.81	0.92

For **RQ2** occupancy detection and temperature setpoints can be used for qualifying the heating response as shown in Fig. 11. Classes for cooling and heating operations based on user presence in a building office.. Basically, the class A system has a better response than class B because it is activated closer when occupancy is detected, the same occurs when there is no occupancy and the heating is turned off, therefore, the responsiveness of the system can be considered to compare different scenarios effectiveness. For **RQ3**, in the office. Fig user occupancy detection appears again, and it is also identified in order to control heating response. For **RQ5**, the classes and function ”1.1 Emission control” described in Table 10 can be adapted to scenarios in order to compare different heating controller solutions.

3 RESEARCH METHOD

This chapter presents the German Use Case by showing an adapted example of the German schedule, after that the Scenario Comparison method shows the method followed to compare smartphone and other scenarios heating responses. Next, the Building Automation Scenarios considered in this work are explained, and the implementation of the tool described. Finally, the Solution Evaluation describes the use cases considered in this work.

3.1 German Use Case

The following context was adapted from Sangogboye (2015) regarding the German BAS user requirement on a weekday:

- The user starts sleeping at 1:00am and wake up at 7:00am. Therefore, the heating is configured in the “sleeping mode” between the interval 12:00am - 6:00am.
- The occupant leaves the place at 8:00am, and arrive home at 4:30pm. Therefore, the heating is turned off at 8:00am and starts heating the house at 3:30pm
- It is supposed that it takes 30 minutes for the user to arrive home from work. Therefore, the user leaves the working place at 4:00pm.

From this description of the German use case, it is noticed that user occupancy, location and sleeping/awakening activities have to be identified.

3.2 Scenario Comparison

In this section, the process followed for comparing the heating configuration scenarios is analyzed. This section explores **RQ2**, and in the Fig. 12, the research process is shown in a diagram form.

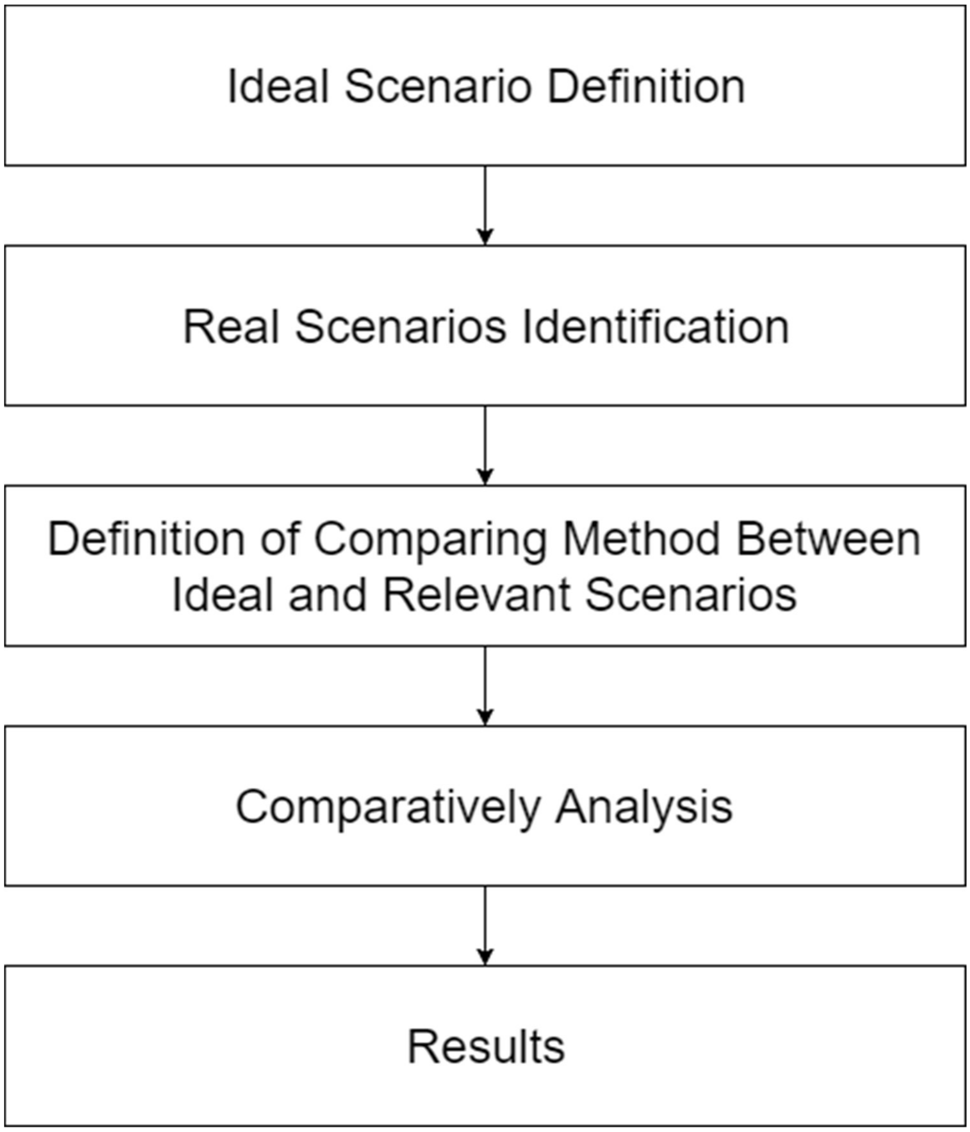

Fig. 12. The research process for scenario comparison.

From the user context point of view, the *Ideal Scenario* occurs when the user context is detected precisely, and it describes the current user situation or activity, so it is a theoretical scenario where the user is 100% sensed and activities are correctly identified. On the other hand, *Real Scenarios* would not have the same user context coverage as the ideal one due to sensor limitations.

The heater operation response is based on the user context, as sensed information is converted to changes in the environment. For this reason, unmatched ideal and detected user contexts will also imply in different heating responses.

The most relevant user context for heating controller involves user occupancy as explored in sections 2.3.2 and 2.3.5 as the purpose of the heater is to set specific temperatures which guarantee user comfort, and if the user is not present at home, the heater should lower down temperature in order to save energy. Additionally, the heater should not only operate when the user is home, but it should also prepare the environment beforehand, so that the user has the best comfort at home as shown in Fig. 11. These relationships show that heating responses can be mapped to specific user contexts, as both of them are related to each other.

The heater is considered to operate in three modes (or setpoints): Normal Operation (NO) with setpoint at 21ºC, Lowered (LO) with setpoint at 17ºC and OFF with setpoint at 5ºC. These temperatures can be set for a day where the temperature varies from 5ºC to 12ºC. In the ideal scenario, the following user contexts can be related to the setpoints:

- NO: user is at home and awake, arriving home or waking up soon. The last two contexts show that the heater response occurs before the user awakes or arrives home in order to condition the user's environment.
- LO: user is sleeping or preparing to sleep. The heater in this situation responds before the user start sleeping in order to prepare the environment.
- OFF: user is outside home.

Siemens (2012) and Sangogboye (2015) also use setpoints and user context descriptions similar to the ones proposed.

To describe operation modes through the day, intervals can store the start and end times of operations during the day. These intervals duration when summed must equate the duration of the day because there are no other possible states for the heater

The ideal and real scenario can be compared by mathematical interval theory based on intersection and exclusion. Therefore, during the day if the setpoints of the ideal and specific scenario match, the real scenario is responding according to what is expected, otherwise, an error is occurring. Fig. 13, illustrates how interval comparing work where green is a determined operation mode and yellow a different one. Additionally, the first line corresponds to the ideal operation and the second to the detected operation mode. As it can be seen, two different errors were generated and represented by the color red and blue. The first error occurs between *t1* and *t2* interval where the detected operation mode should be green, but yellow was detected, and the inverse occurs between *t3* and *t4*.

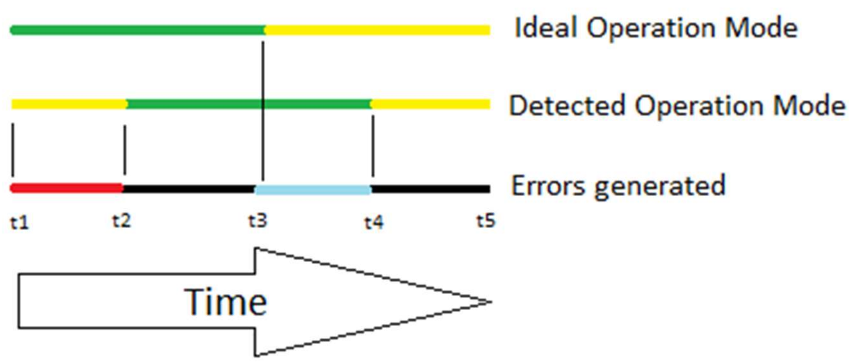

Fig. 13. Interval comparing and error generation.

For this example, the error duration in red can be calculated by subtracting t2 from t1, and in blue by subtracting t4 from t3. Therefore, if the ideal and detected operation modes intervals are known, the errors can be calculated computationally.

There can be different types of errors, and they are defined as combinations between detected and ideal operation modes. For each ideal operation, there are two other types of errors which can occur, for instance if the NO operation is the ideal one, two different errors can occur in the detected operation mode: LO and OFF. For this reason, 6 types of errors can occur in the total.

Scenarios with lower errors have better efficiency. It is also relevant to mention that Siemens (2012) also uses a similar performance comparison principle based on operation modes and intervals, as higher-level classes have more responsive setpoints regarding time as discussed in 2.3.5.

Table 12 describes six possible errors that are generated when ideal and real heating responses are compared. The error type describes the ideal and detected operation modes, e.g., in EHNO-OFF, NO is the ideal operation and OFF is the detected one. The table also describes the ideal and detected contexts for each error type.

Table 12. Six possible errors occurrence heating controller when ideal and detected contexts are considered. Where EHNO-OFF means Error Heating Normal Operation (ideal) - OFF (detected)

Error type	Ideal Context	Detected Context
EHNO-OFF	at home awaken or pre-heating	outside home
EHNO-LO	at home awaken or pre-heating	user is sleeping or sleeping soon
EHOFF-NO	outside home	at home awaken or pre-heating
EHOFF-LO	outside home	user is sleeping or sleeping soon
EHLO-NO	user is sleeping or sleeping soon	at home awaken or pre-heating
EHLO-OFF	user is sleeping or sleeping soon	outside home

The unit of each error type is minutes, and the calculation of these errors during the day can be performed by summing and storing them in variables, as they can occur more than once per day. Therefore, the total error can be calculated by Eq. 1 where all errors are considered and summed through the day:

$$TotalError(minutes) = \sum EHNOOFF + \sum EHNOLO + \sum EHOFFNO + \sum EHOFFLO + \sum EHLONO + \sum EHLOOFF (1)$$

Finally, the efficiency for a specific scenario during the day can be obtained by extracting the percentage of the Total Error obtained in Eq. 1 in relation to the period of the day in minutes which is 1440 as shown in Eq. 2:

$$Total\ efficiency\ (\%) = 100 \times \left(1 - \frac{T.\ Error}{1440\ minutes}\right)\ (2)$$

In this chapter, it was presented a computational model for calculating errors and efficiency by comparing a real and ideal scenario considering user contexts, so **RQ2** was explored.

3.3 Building Automation Scenarios

Besides the current implementation, which is being investigated, and scenario, three scenarios were simulated based on Siemens (2012) classes:

- *No BAS* (Class D): there is no heater controller, and the user set the radiator knob at a certain level, and no further control is performed. There is absence of sensors and actuators.
- *Fixed Schedules* (Class B): the heater controller is based on fixed schedules set by the user. The user can program outside home and sleeping intervals. No further sensors and actuators are used.
- *Presence* (Class A): the heater controller turns on and off based on the user's arrival home (e.g. through motion sensor), and departure (e.g. through exit button near to the door), respectively. However, there is no sleeping detection.

The ideal scenario was acquired in the end of the day based on the smartphone sensors information. As it will be shown, one of the problems for generating the ideal scenario is, that it would be necessary to predict some user actions, so it would be impossible to generate the ideal scenario in real time. Therefore, the smartphone was not capable to follow precisely the ideal scenario as it will be discussed in section 5.

3.4 The Developed Platform

The aim of the current project was to achieve a Class A solution based on functions 1.1, 1.5, 5.1, 5.2, 7.1 and 7.2 specified in Table 10 (page 34). In addition to that, another function was added for controlling appliances:

- 8. Appliances - Occupancy Control
  - Class D, C, B - Manual on/off
  - Class A - Turning on specific appliances when the user arrives home. Turning off appliances when the user is not home.

This project also aims to identify when the user is sleeping and awakening, and the ideal scenario is based on Table 12, and consecutively on Fig. 11. Therefore, the system configures heating setpoints one hour before the user's arrival home, sleeping, and awakening to condition the environment:

- When the user is going to sleep, the system should lower the temperature of the place.
- When the user is awakening or arriving home, the system should maintain normal temperature.
- When the user is identified outside home the heater response should be immediate and turn off (different from Fig. 11) because in the current scenario it is considered only one person and only one room to control.

The following subsections detail the resources used for replication of the solution and detailed description for the smartphone and server application implementations.

3.4.1 Hardware and Software Resources

The purpose of this section is to explain the hardware and software technologies used for implementation of the platform. Fig. 14 shows the components, modules and sensors which were used in the current approach for the smartphone and server.

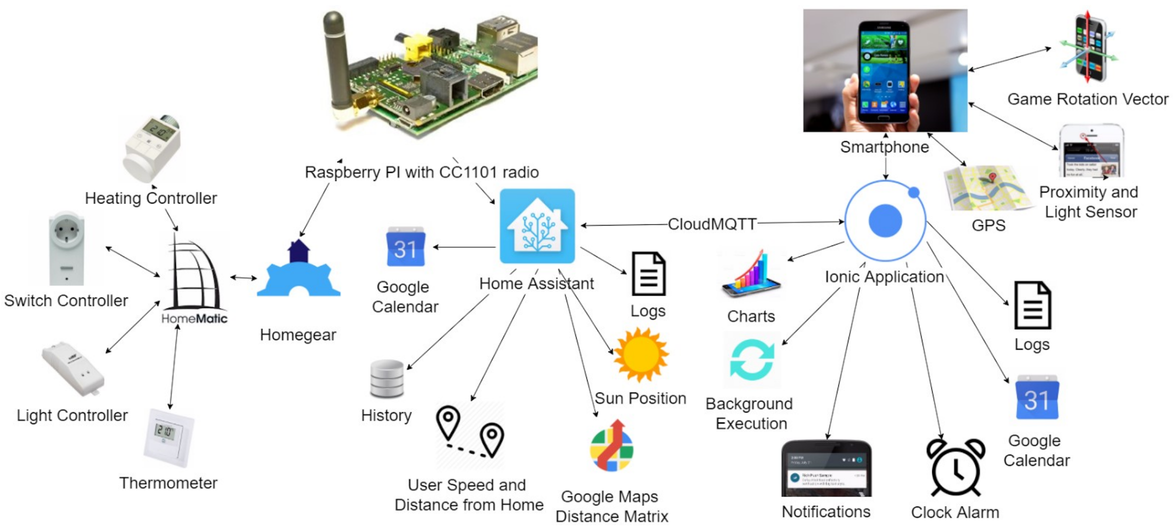

Fig. 14. The current implementation.

Table 13 and 14 show the hardware and software resources used in this project, respectively.

Table 13. Technologies chosen for hardware implementation.

Resource type	Technology Used	Reason of choice

Home Automation Protocol and Devices	HomeMatic: heating, switch, light and thermometer.	Found more devices in retail shops (ELV[12], Conrad[13]), so it was assumed that it would be more accessible for German residents.
Smartphone Sensors	GPS, Proximity, Light. Accelerometer and Gyroscope	Based on literature review sections 2.3.2 and 2.3.3.
Microcontroller	Raspberry PI + radio receptor [14]	Cheap, and highly used

Table 14. Technologies chosen for software implementation.

Resource type	Technology Used	Reason of choice
Home automation platform	Home Assistant	Through documentation it was noticed easier integration of charts, google calendar, google maps distance matrix in order to implement the tool.
3rd party software for communication between the home automation platform and devices	Homegear[15]	In order to connect HomeMatic devices with home assistant Homegear has to be installed as it is recommended in HomeAssistant forums.
Smartphone Application	Apache Cordova + Ionic + AngularJS	Supports portability and future expansion of iOS and Android solutions in the same project
Communication protocol between	MQTT	According to MQTT Website, this protocol is ideal for mobile applications because of its low power usage, minimized data packets

[12] https://www.elv.de/
[13] https://www.conrad.de
[14] http://busware.de/tiki-index.php?page=COC
[15] https://www.homegear.eu

Smartphone and Server		in message exchange. Additionally, the possible distribution of messages to many receivers which listen to specific topics.

Additionally, Table 15 shows the smartphone and server implementation details for developing the functions described in Table 10. One limitations for heating in “1.1 Emission Control”, was that winter and summer compensations for the heater set points were not implemented. Another limitation for lights in “5.1 Occupancy Control” was that occupancy was detected only when the user arrives home, and leaves home, and not when he/she moves from one room to another so that lights are dimmed off after a period. Although, both of these limitations were recommended in the Siemens report (Siemens, 2012).

Table 15. Description of the methods used for implementation of Siemens Report function controls

Function	Smartphone App	Server App
1.1 Emission control	User location (GPS coordinates) and user activity recognition (sleeping, awakening)	User presence and direction (GPS coordinates) and activities detected from smartphone.
1.5 Intermittent control of emission and distribution	Party event in Google Calendar	Google Calendar party verification
5.1 Occupancy Control	same as 1.1	same as 1.1
5.2 Daylight Control	Not Applicable	Relative sun position (below or above horizon)
7.1 Fault detection + diagnosis	Logs	Logs

7.2 Reporting energy use + improvement possibility	Interval configuration for Fixed Schedules simulation. Results comparing different scenarios shown through charts.	Devices response history, user activities intervals, and results comparing different scenarios calculations.
8 Appliance Control	same as 1.1	same as 1.1

Furthermore, APPENDIX 1 shows the sequence diagrams for the most important operations in the system. Also, the code for the smartphone application and home assistant configurations is available on GitHub[16].

3.4.2 The Smartphone Application

The smartphone acted as a client which sends and receives messages through MQTT to and from the server. The mobile software was implemented by using the framework Apache Cordova with Ionic SDK and AngularJS as the MVC. The sensors used in the smartphone were: GPS, Light, Proximity and Game Rotation Vector (accelerometer and gyroscope). Some modules were also included in the approach as the MQTT, Charts, Background Execution, Notifications, Clock Alarm, Google Calendar and Logs. Fig. 15 and 16 show all user interface screens in the smartphone application. As shown in the user interface, it is possible to start the system, configure MQTT and GPS, add intervals to simulate the sleeping and outside home schedules, and check results which shows the scenarios comparison regarding errors and efficiency. There is also a Notification area where the user can have some feedback with system errors, GPS coordinates, sleeping and awaken activities identified.

[16] https://github.com/hnrqer/Smartphone-BAS

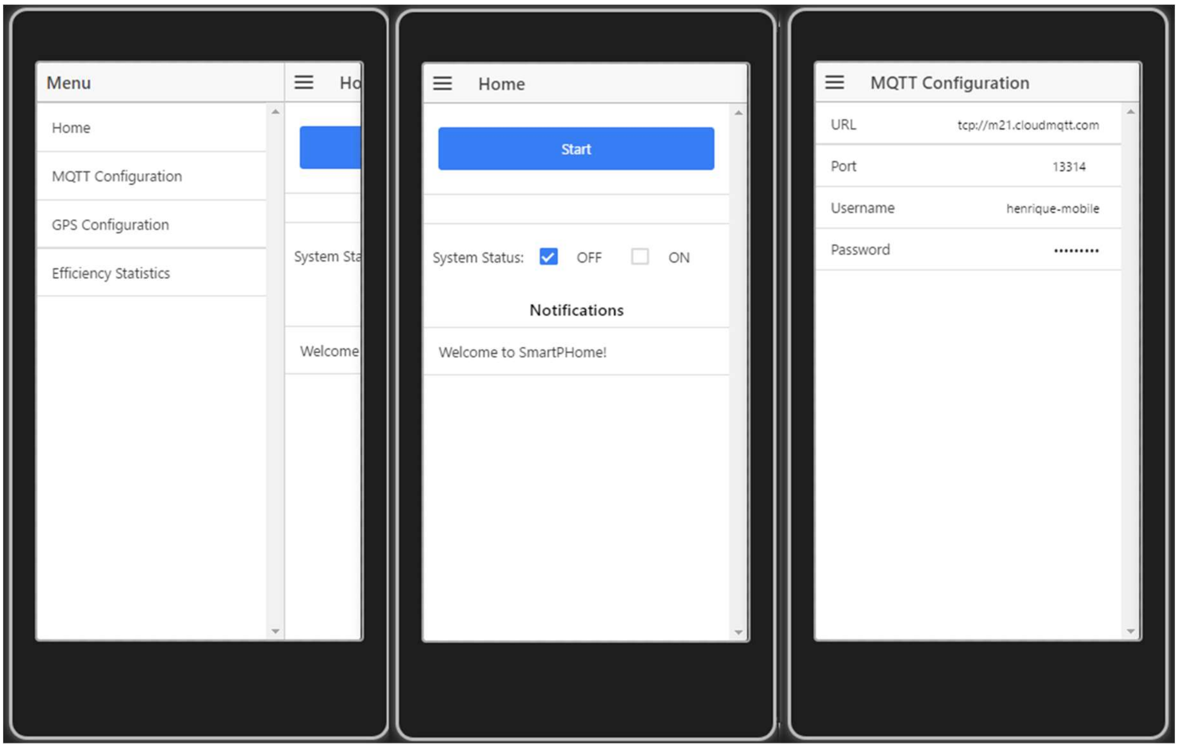

Fig. 15. Smartphone application user interface: part I

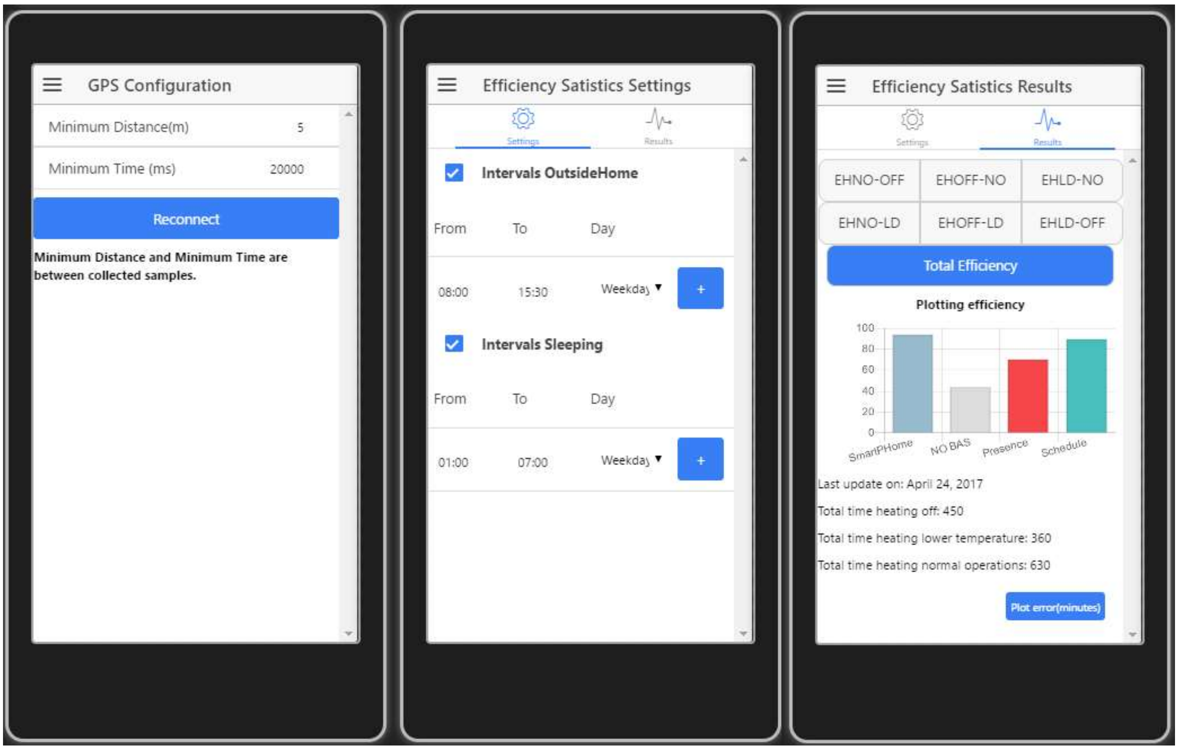

Fig. 16. Smartphone application user interface: part II

For presence detection, the GPS sensor was used and only activated when the user moves the smartphone so that energy in the device could be saved. For activity recognition sleeping/awaken states were detected through the game rotation vector, infrared and light sensors. For this purpose, it was assumed that when the user is going to sleep the smartphone is left under the pillow or flipped so the screen touches the mattress. When the user is waking up the smartphone is left in a position where nothing is covering the front screen, and if there is (e.g. the smartphone is in the pocket), the position of the smartphone is not lying down. It was also assumed that the native alarm clock from the smartphone is used, so it is possible to anticipate when the user is going to awake. The next alarm clock is identified only when the user is going to sleep.

Logs were registered and updated to the user's view. If the system crashes there is also a log file which reports the last messages and errors.

For simulating the Fixed Schedules scenario, the user can configure intervals where he/she assumes to be sleeping and outside home. Charts are available to see results regarding the scenario comparison. Although, the computational process for scenario comparing is performed in the server-side, and sent through MQTT to the smartphone

All implementation was performed in an Android device (Galaxy S5) where the application ran in background, for this purpose a service was created. It is possible to configure MQTT connection and GPS (interval and distance filters), and the app also auto reconnects if the user changes from Wi-Fi to Mobile data and vice-versa. Finally, the smartphone sends the following messages through MQTT to the server: GPS coordinates, sleeping, awakening, alarm clock, and scheduled intervals.

3.4.3 The Server Application

The server integrates Raspberry PI with a radio receptor module. The Raspberry PI acted as the server in which Home Assistant was installed. HomeMatic devices were used in order to control heating, lighting and appliances. The communication between Home Assistant and HomeMatic devices was integrated through Homegear which was also installed in the Raspberry PI. Home Assistant uses the following modules: Google Calendar, History, User Speed and Distance, Google Travel Distance Matrix, Sun Position, Logs and MQTT. Fig. 17 shows the user interface in the server application. It is possible to observe the following modules represented by white blocks: climate involving setpoints and currently temperatures for the heating system, lights, detected activities calendar, proximity and appliances. Also in the top of the screen there are some other information regarding sun position, user occupancy, humidity (based on a climate sensor), user speed, outside weather, temperature in the bedroom, and travel times by bike, car and walking.

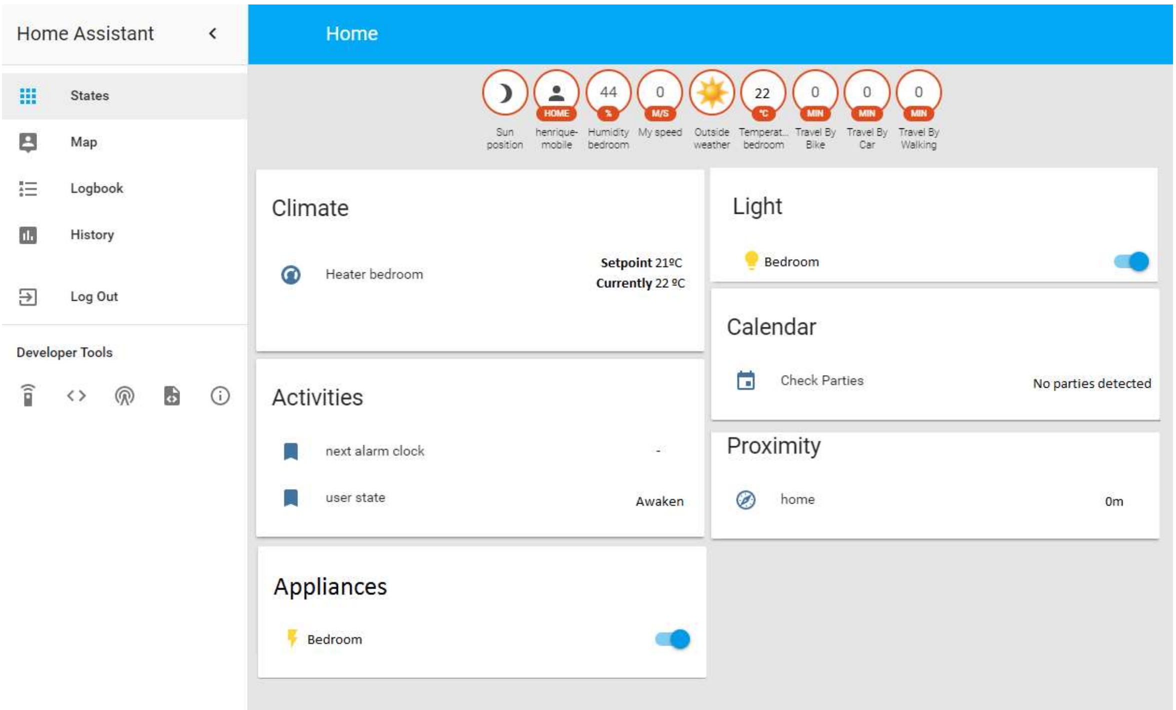

Fig. 17. User interface of the Smartphone application

For presence detection, the user's distance from home is calculated. The user is not home if the distance is higher than 100m, and in this case appliances, lighting and heating are shut down and the sleeping/awakening states are not verified. If the user is identified at home, heating is set to 21ºC, appliances are turned on and if the sun position is below horizon, lights are also turned on.

The user direction is also identified. If the user direction is towards home the state arriving home is identified, and if the user is arriving in less than 60 minutes, the heating controller is set to 21º C. If there are no GPS updates from the user smartphone in 3 minutes during his/her arrival, the user is considered to be not home.

If the user is identified as sleeping, the heating controller is set to 17º C, and all lights are dimmed off and appliances turned off. The user is expected to awake when the next alarm clock is triggered, or when an awakening state message is received. The heater is set to 21ºC 60 minutes before the next alarm clock is triggered. If an awakening message is received, the heater is set to 21ºC immediately.

If a party is identified, the heater is set to 17ºC as people's body already produces heat. If the user is throwing a party, activities (location, sleeping, awaken) are not verified

Logs are registered through files, for crashes verification, and in the front-end. A weekly history also shows the response of devices and components.

User activities time are stored, so it is possible to identify user's presence and sleeping intervals. By using these intervals, it was also calculated the ideal situation in which the heating should respond with 21ºC, 17ºC and off (5ºC). Finally, the server calculates at the end of the day and sends through MQTT efficiency and errors for all scenarios.

3.5 Solution Evaluation

Two use cases were explored for evaluating heating efficiency: one based on a strict user behavior where the user follows the schedule proposed, and a second one where the user has an unpredictable behavior. A third use case was explored in order to show the benefits of lights and appliances. All use cases were performed in a bedroom where the user also sleeps, and heating, lighting and appliances were controlled.

In the first use case, it is supposed that the user has followed the German Use Case described in section 3.1 strictly, and configured the smartphone schedule intervals in the Fig. 16 (second smartphone screen), accordingly. In this case, the schedule approach matches exactly the ideal heating response. Additionally, if the user configured the interval schedules on the smartphone in a different basis, even daily, the system would use these intervals for calculating the interval schedule approach errors and efficiency.

In the second use case, it is supposed that instead of following the Fixed Schedule described in the German Use Case section 3.1, the user behavior was unpredictable, so the German

Use Case schedules were not followed. For that purpose, the user behavior was modelled by delaying all user action which would normally be followed by the user schedule described in 3.1. The user started sleeping later at 2:00am, and configured the alarm to trigger at 8:30am, so the ideal case the heating should lower the temperature to 17ºC at 1:00am and start heating normally (21ºC) at 7:30am. The user also decided to work later at 9:30am, and arrive home later at 5:30pm on that day. In this case, the heater should turn off at 9:30 am, and operate normally (21ºC) at 4:30pm.

The third use case was introduced to explore the benefits of lights and appliances control related to comfort, and in this case energy efficiency comparisons with other scenarios were not performed due to the delimitations presented in section 1.3. This use case was performed on the weekend where the user goes to sleep at 2a.m. and wakes up at 11:30a.m. The user also leaves home at 7:00p.m. and goes back home at 9p.m.

4 RESULTS

This section presents results gathered from the use cases presented in section 3.5.

4.1 Use Case 1: Strict behavior

The Fig. 18 describes the ideal heating setpoints and the smartphone based one. The smartphone approach would differ from the ideal setpoints only by two errors: the lowered temperature (17ºC) one hour before sleeping and the normal operation (21ºC) 30 minutes prior to user's arrival. The Fig. 19 shows a response collected by home assistant history[17] in order to show changes the room temperature and the smartphone heating setpoints solution.

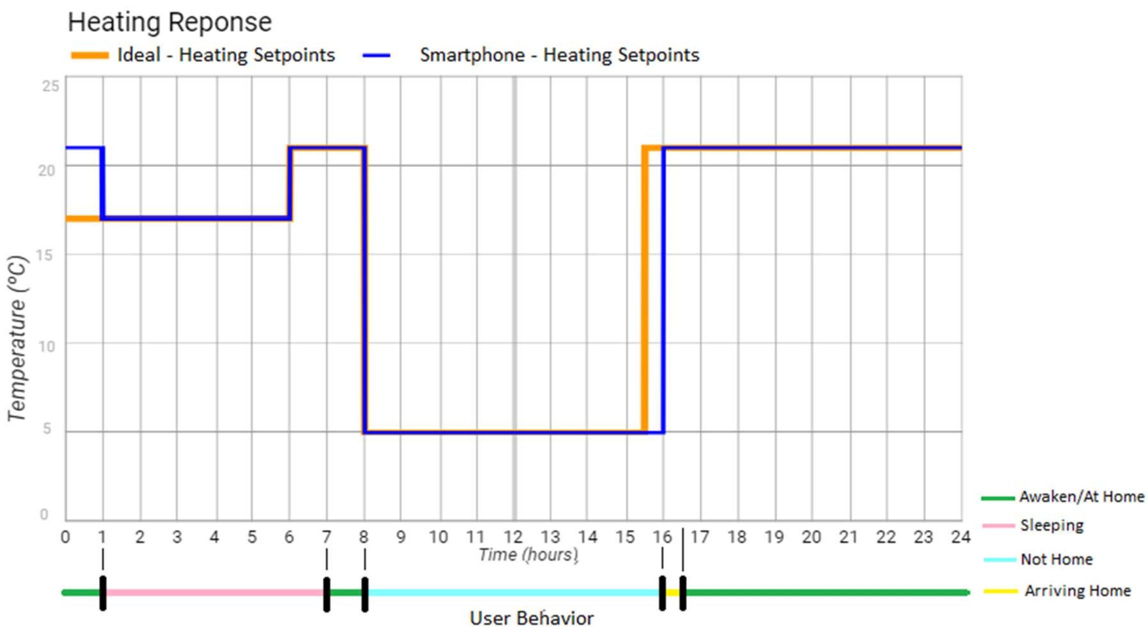

Fig. 18. Use Case 1: Ideal heating setpoints vs. Smartphone heating setpoints.

[17] https://home-assistant.io/components/history/

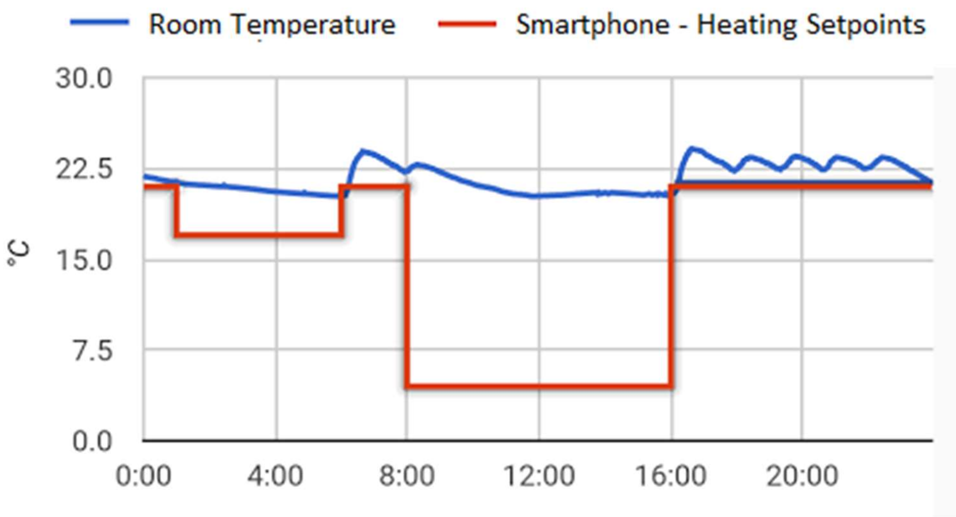

Fig. 19. Use Case 1: Temperature and heating setpoints in the smartphone based approach acquired by Home Assistant history.

Table 16 shows the other scenarios simulated response. To process these results, the errors described in Table 12 were calculated, and the total error and efficiency was based on Eq. 1 and Eq. 2. It is also possible to observe that by using the proposed comparing method and for this specific scenario, the smartphone approach can be 50% more efficient when compared to the No BAS scenario and 23% more efficient when compared to the Presence scenario. On the other hand, the schedule scenario is the best one in this case. The total operation time for NO is 630 minutes, LO is 360 minutes and OFF is 450. Additionally, Fig. 20 shows the heating response scenario comparison in the smartphone by showing errors and performance regarding all scenarios.

Table 16. Use Case 1: Results between different scenarios.

Error Type	Smartphone	No BAS	Presence	Schedule
EHNO-OFF (minutes)	30	0	60	0
EHNO-LO (minutes)	0	0	0	0
EHOFF-NO (minutes)	0	450	0	0
EHOFF-LO (minutes)	0	0	0	0

EHLO-OFF (minutes)	0	0	0	0
EHLO-NO (minutes)	60	360	360	0
Total Error (minutes) / Total Efficiency (%)	90/93.8%	810 /43.8%	420/70.8%	0/100%

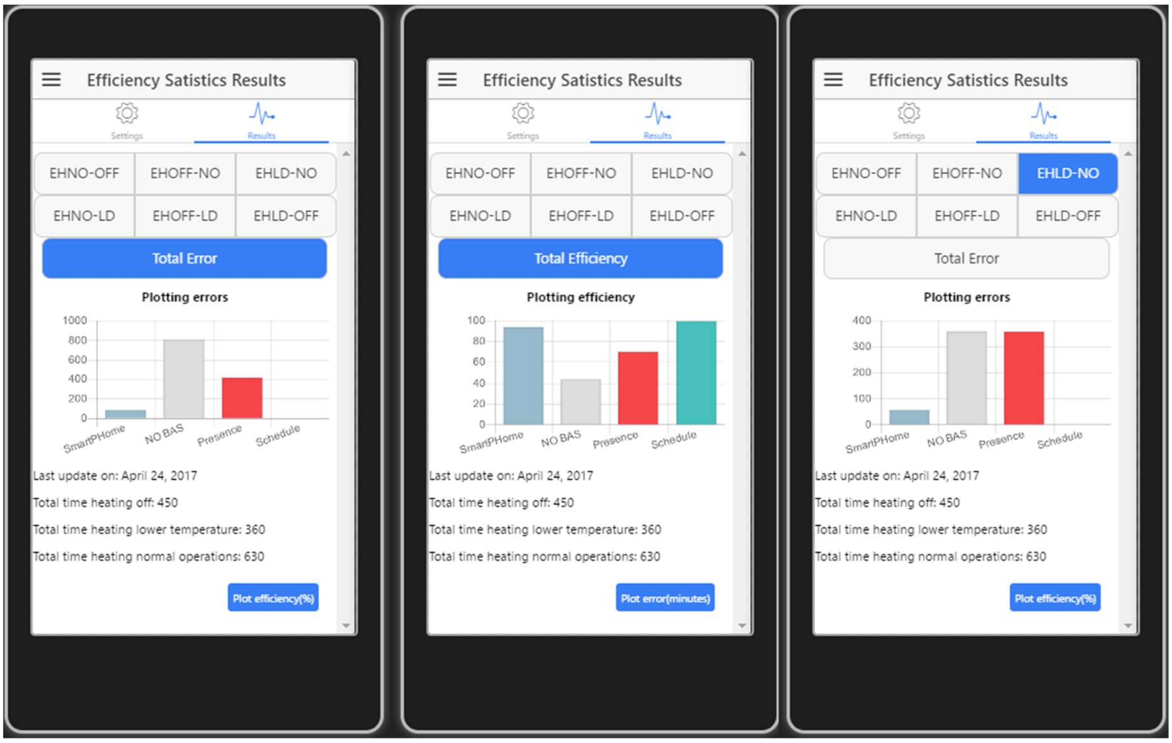

Fig. 20. Use Case 1: Displayed results on the smartphone regarding all scenarios. Comparing total error, total efficiency and the error EHLO-NO in minutes

4.2 Use Case 2: Unpredictable behavior

The Fig. 21 describes the ideal heating setpoints, the schedule one and the smartphone based one. In the smartphone approach, the same type of errors which were mentioned in the use case 1 occurred, but for the fixed schedule scenario, some types of errors occurred. The Fig. 22 show changes in the real room temperature for that day, and the smartphone heating setpoints solution. Important to notice that in that specific day outside temperatures were higher than the usual.

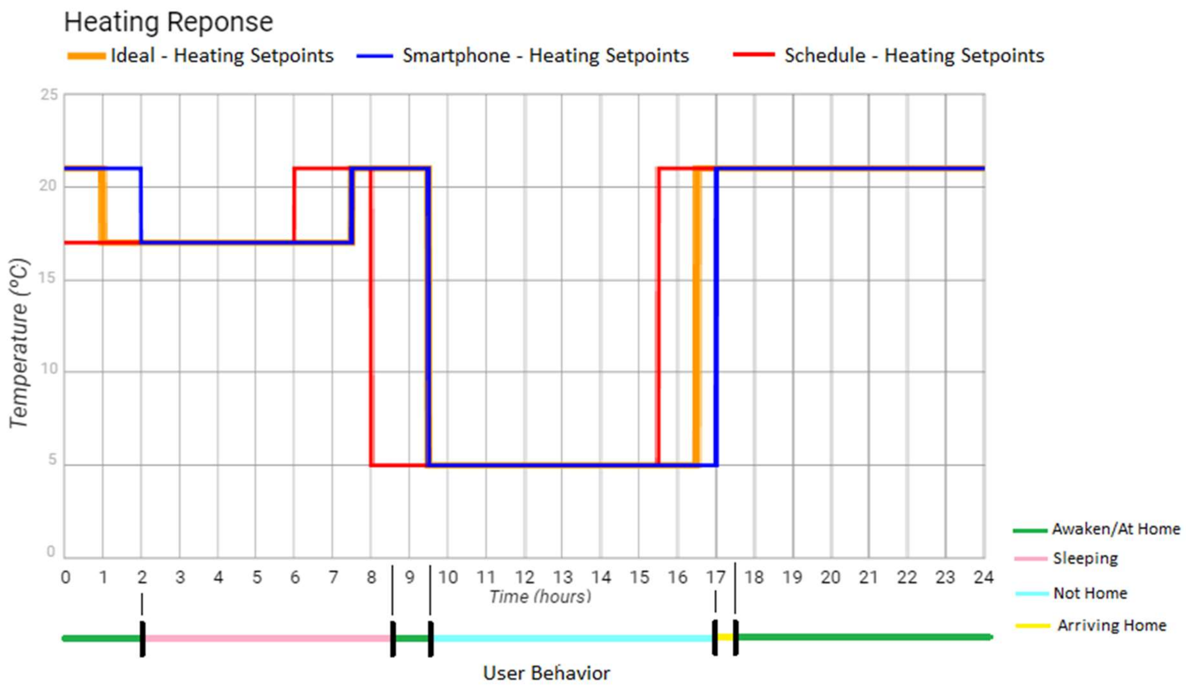

Fig. 21. Use Case 2: Ideal heating response vs. Smartphone heating response vs schedule heating response.

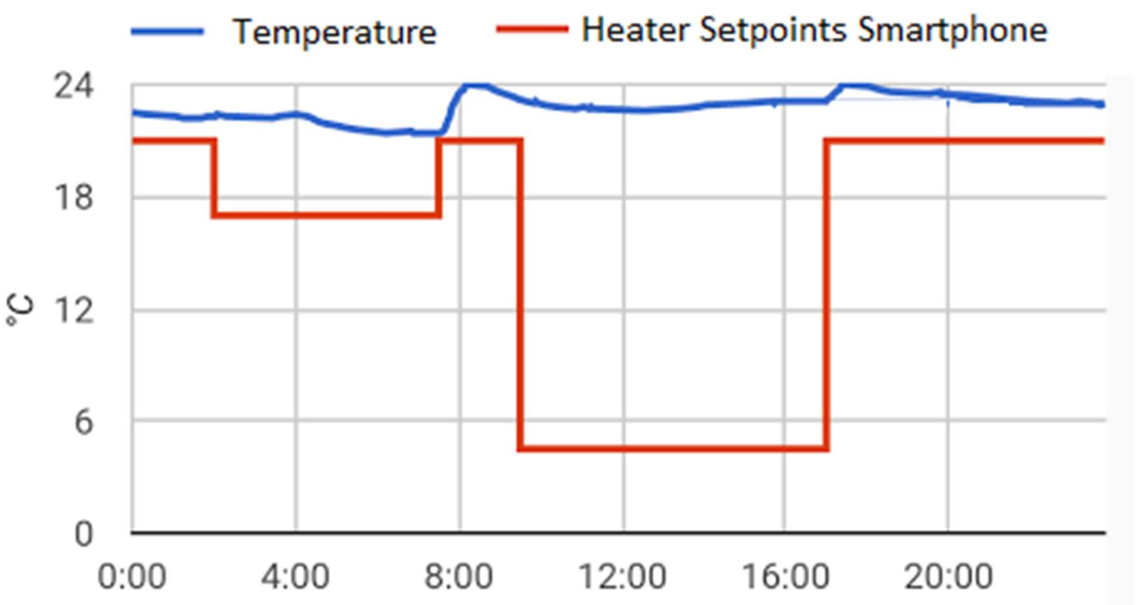

Fig. 22. Use Case 2: Temperature and heating setpoints in the smartphone based approach acquired by Home Assistant history.

Table 17 shows the other scenarios simulated response. It is possible to observe that in this use case the smartphone approach was the best one when compared to other solutions. It was 14% more efficient than the fixed schedules one. The total operation time for NO is

650 minutes, LO is 390 minutes and OFF is 420. Additionally, Fig. 23 shows the heating response scenario comparison in the smartphone by showing errors and performance regarding all scenarios.

Table 17. Use Case 2: Results between different scenarios.

Error Type	Smartphone	No BAS	Presence	Schedule
EHNO-OFF (minutes)	30	0	60	90
EHNO-LO (minutes)	0	0	0	60
EHOFF-NO (minutes)	0	420	0	60
EHOFF-LO (minutes)	0	0	0	0
EHLO-OFF (minutes)	0	0	0	0
EHLO-NO (minutes)	60	390	390	90
Total Error (minutes) / Total Efficiency (%)	90/93.8%	810 /43.8%	450/68.7%	300/79.2%

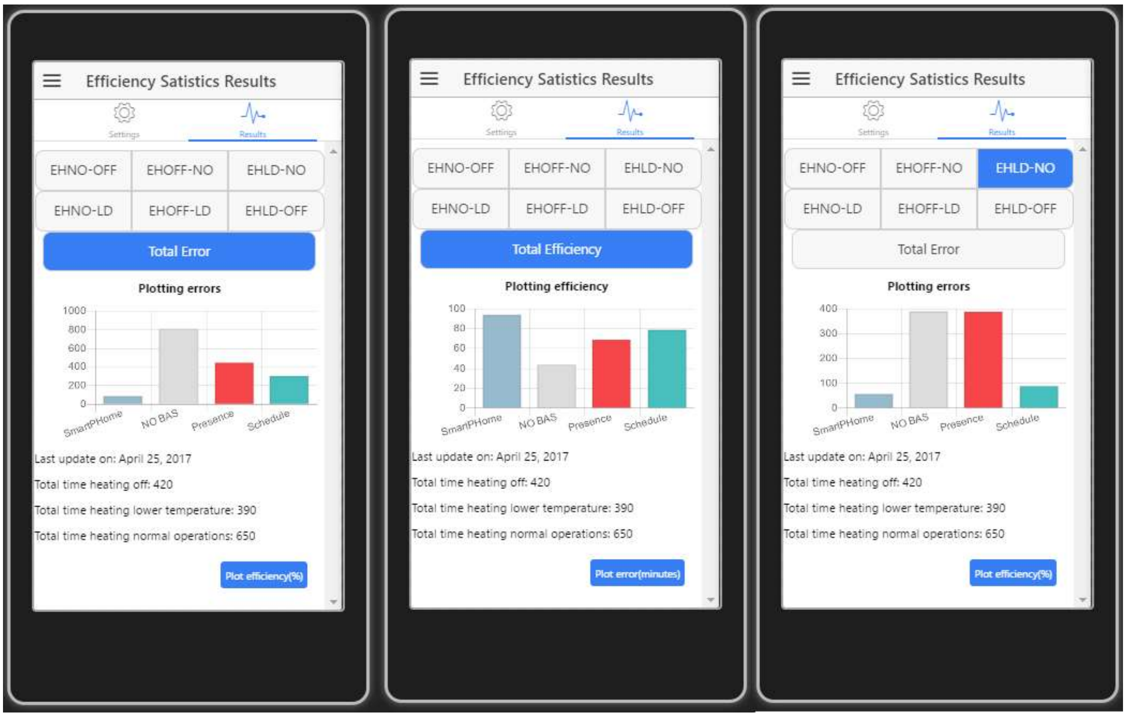

Fig. 23. Use Case 2: Displayed results on the smartphone regarding all scenarios. Comparing total error, total efficiency and the error EHLO-NO in minutes

4.3 Use Case 1 and 2 Errors Summary

According to the results shown in Table 16 and 17 it is possible to observe that the No BAS scenario could not identify sleeping, neither outside home intervals, as the radiator valve is set to a fixed value. Therefore, this case study was associated with the errors EHOFF-NO and EHLO-NO, and they represent the total operation time of the ideal situation for the heating off and lowered operations respectively.

Fixed Schedules could have all types of errors. For example, the user believes he/she is going to sleep at 11:00pm every day, but for a specific day the user goes to an event or party with friends outside home, in this case the error EHOFF-LO is increased.

The Presence scenario cannot identify the user sleeping activity neither when the user is arriving home, so this scenario is mostly affected by EHLO-NO and EHNO-OFF.

The smartphone approach is mostly affected by three types of errors EHNO-OFF, EHLO-NO and EHOFF-NO. EHNO-OFF occurs if it takes less than 60 minutes for the user arriving home, so the heater is set to 21ºC only when the arriving home state is identified, but in the ideal case, it should be set 60 minutes before the user is at home. EHLO-NO occurs because this approach cannot predict when the user is going to sleep, so the heater response does not lower down 60 minutes before the user sleeping. EHOFF-NO occurs when the user is going to his/her home direction, but actually goes to another place which is in the same direction, and the user goes home only later. Therefore, the user state would change from arriving home to not home, and mislead the system to turn on the heater when it was not supposed to.

4.4 Use Case 3: Lights and Appliances Control

Fig. 24 and 25 shows the results from home assistant user state identification, appliances response, sun position, lights response, distance from home, duration to go back home by car, bike and walking and the heating response. Appliances turn on after the user awaken state and arrival, and turn off when the user is sleeping, and not home. Lights turned on when the user arrived as the sun position was below horizon. The arriving state is shown by the yellow block in the user state and it represents around 10 minutes.

Fig. 24. Home assistant lights and appliances control, and other modules - part 1.

Fig. 25. Home assistant lights and appliances control, and other modules - part 2.

5 ANALYSIS AND DISCUSSION

This section reviews all research questions and it also explores **RQ1** for investigating the benefits of smartphones and user contexts in BAS. Regarding the sub research questions:

- **RQ1** (main Research Question): How energy efficiency is affected when the user context and introduction of smartphones are considered for German residential BAS?
    - **Answer:** This is explored through this whole section
- **RQ2**: What methodology can be used in order to qualify the heating response?
    - **Answer:** Based on section 2.3.5, occupancy and temperature setpoints were applied to qualify different systems response based on classes. Therefore, the method developed in section 3.2 was based on this information.
- **RQ3**: Which user's contexts are more relevant to be identified in order to control heating, lighting and appliances usage?
    - **Answer:** Sections 2.3.2 and 2.3.5 covered this research section, so user occupancy was used for controlling heating, lighting and appliances
- **RQ4**: Which sensors and algorithms can be used in order to identify more precisely the user context when smartphones are integrated?
    - **Answer:** Based on section 2.3.3 accelerometer was used for user activities and posture detection, and GPS for user location and transportation detection. Also, logical inference through thresholds was used for developing the tool.
- **RQ5**: Which scenarios are more relevant in order to compare energy efficiency in BASs specifically when the user context is taken in account?
    - **Answer:** Section 2.3.5 presented classes and functions which were adapted in order to create the relevant scenarios.

As observed in the results section the smartphone approach when compared to the Fixed Schedule reveals a unique opportunity for BASs when the users can not estimate the behavior through schedules. This situation is even more relevant for weekends and vacation periods when the user has no regular routine at all. The efficiency for the smartphone approach when compared to Fixed Schedule would depend on the user's strictness on following the intervals configured. Although, the implementation of the Fixed Schedules is simpler as it would be possible to implement it only with a heater controller, as far as this device has schedule configuration, but this would decategorize this scenario as a BAS.

Presence scenario relies not only on the same controllers as the smartphone approach, but also in two more controllers (exit button and motion sensor). It is also possible to identify that this approach would not identify the user sleeping state, and neither his/her arriving home state, therefore, less comfort and efficiency is guaranteed.

The No BAS scenario would only be interesting to choose if the user does not leave home frequently (e.g. the user work at home), but even in this condition the sleeping state would not be identified. The user could also set manually the heating valve when planning to sleep, but this would depend on the user’s strictness on following this other behavior, and it would not be possible to guarantee a specific temperature without a controller either.

Light and appliances were also controlled in the smartphone scenario. In the No BAS scenario, it would not be possible implement this function. In the Presence and Fixed Schedule scenarios (if the user integrates Raspberry PI and other actuators) it would be possible to implement it, and they would also have the similar issues as there are for the heating controller.

Parties could also be identified by other scenarios as far as they have a system which uses calendar, and is integrated in the home automation platform. The inclusion of this function for smartphones was implemented because of the relevance of Google Calendar in smartphone devices.

Eco-feedback is promoted by efficiency and error results which are shown in the user’s smartphone application so that it is possible to track the relevance of the scenarios according to the user behavior as shown Fig. 20 and 23. After that, the users can understand which solution is more relevant for their behaviors, and maybe change their current BAS approach.

For future works, it would be interesting to apply the proposed system with more samples, and analyze the response through a long period in order to find and consolidate further benefits regarding this approach. It would also be interesting to analyze different types of houses response based on their structure and integration with different BASs.

For optimization of the solution, it would be interesting to include humidity control based on humidex values. Another optimization related to user occupancy detection would be to identify if the user is outside home but inside the 100m perimeter related to his home, as the current system would identify as he/she is still inside it. For solving this issue internet connection recognition from the smartphone to his/her home Wi-Fi spot could be implemented. If the user is connected to the Wi-Fi the system would detect the user inside home, otherwise it would detect the user as outside.

Furthermore, as shown in Fig. 22, it would be interesting to add flexible heating set points as the outside temperature for that day was too high and this solution did not consider this case. The control local loop response could also be analyzed in order to improve the system efficiency by using flexible response times for setpoints, so they wouldn`t be fixed by one hour as it is currently. Although the system would be more complex, it could save more energy and achieve the setpoints with a higher precision. Therefore, this studied could be improved by using for example a fuzzier scheme based on inside and outside temperature and the system control response.

Weather forecast could also be integrated. Additionally, it would also be interesting to extend this research by adding more rooms, controllers, people, and smartphones. Finally, smarter algorithms based on user patterns and supervised learning for user context detection could be implemented in order to improve the systems reliability.

Finally, it would be interesting to analyze the smartphone energy consumption smartphone for executing the current application on different OS and devices.

6 CONCLUSION

In this work, a smartphone was integrated to a building automation system in order to improve the system's energy efficiency. The main focus of the research was exploring the heating efficiency due to its relevance in the household's energy consumption. For that purpose, a report based on the standard EN15232 was followed in order to implement the solution and a computational model which compares the ideal heating response with other solutions response was formulated, and through this model, scenarios and the ideal heating response were compared in order to investigate the contribution of this work.

This work has shown that the integration of smartphones in Building Automation Systems are relevant, and through this approach it is possible to observe improvement of better energy efficiency for the heating controller depending on the user's behavior. Preliminary results analyzed by use case comparison show that heating efficiency can be improved by 14% when compared to the fixed schedules scenario, and by 50% when compared to the No BAS scenario.

For the Economic pillar of sustainability, this work contributed by presenting the smartphone based solution benefits for controlling the heater response which implies in energy savings for the user. Additionally, in this work only one switch, one heater and one dimmer controller were used for managing the environment of a bedroom, and other solutions could require extra sensors implying in extra investments for the user.

For the Environment pillar, thermal and electrical energy are managed so the user is also contributing for less CO_2 emissions. Additionally, if the user requires less devices, there is also an implication in less waste being generated after the life cycle of a device if it is not recycled.

For the Society pillar, the management of lights and appliances for the user can increase comfort. Additionally, through feedback showing all scenarios heating response, users could be educated and change the heating configuration in order to satisfy their needs.

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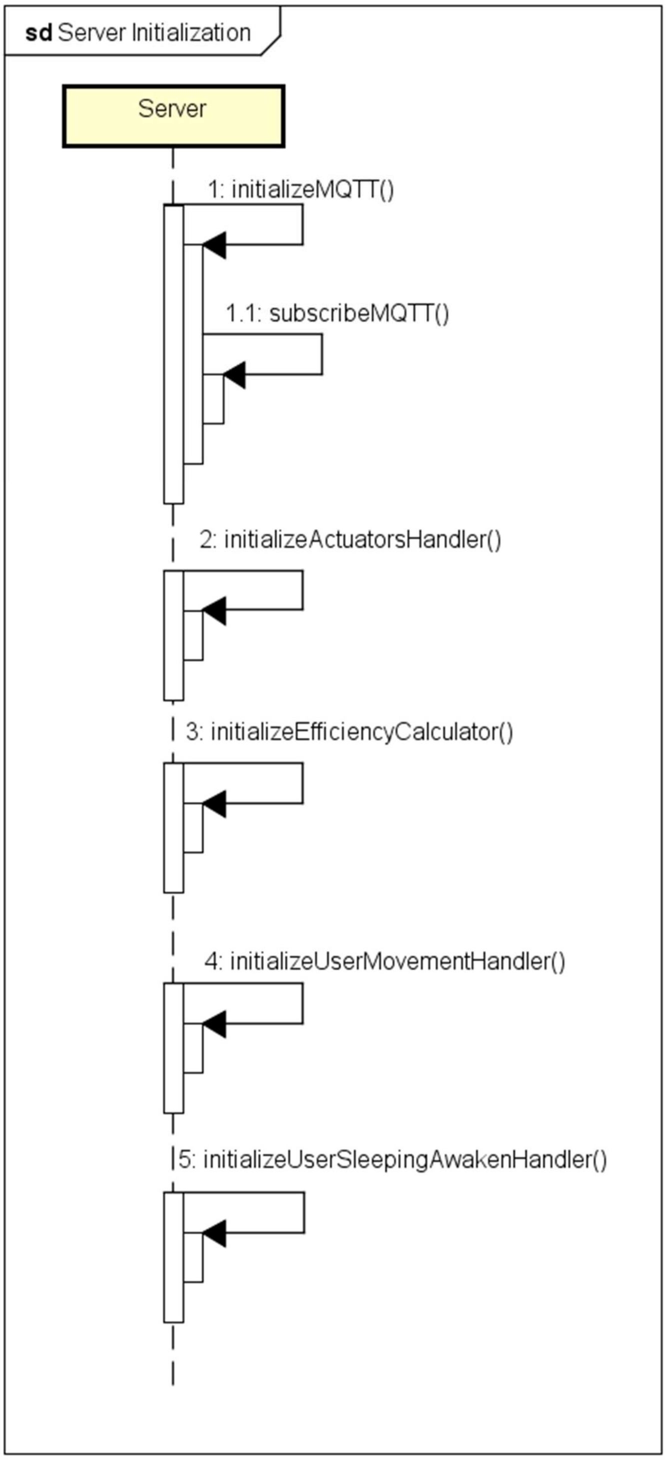
APPENDIX 1. Sequence Diagrams



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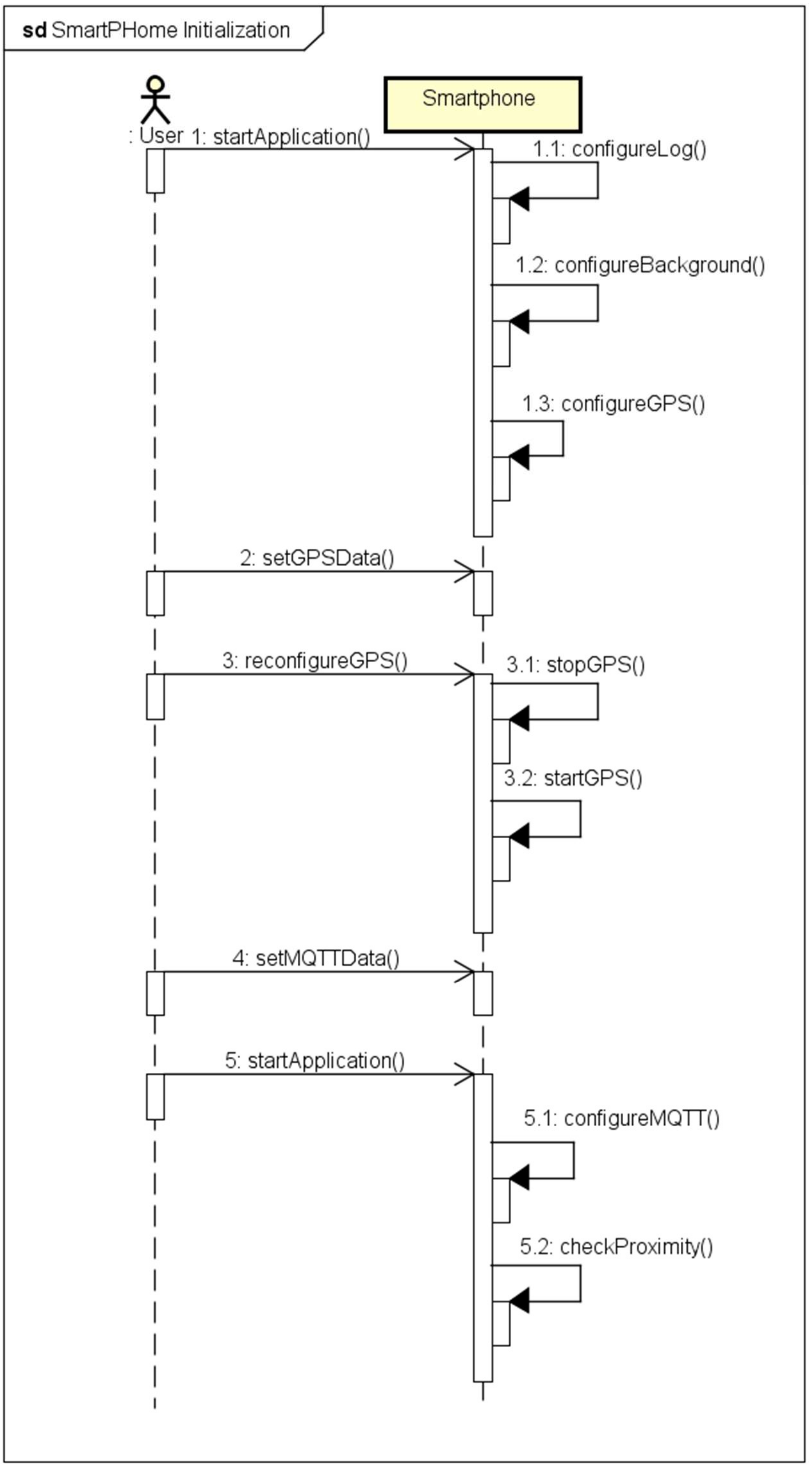

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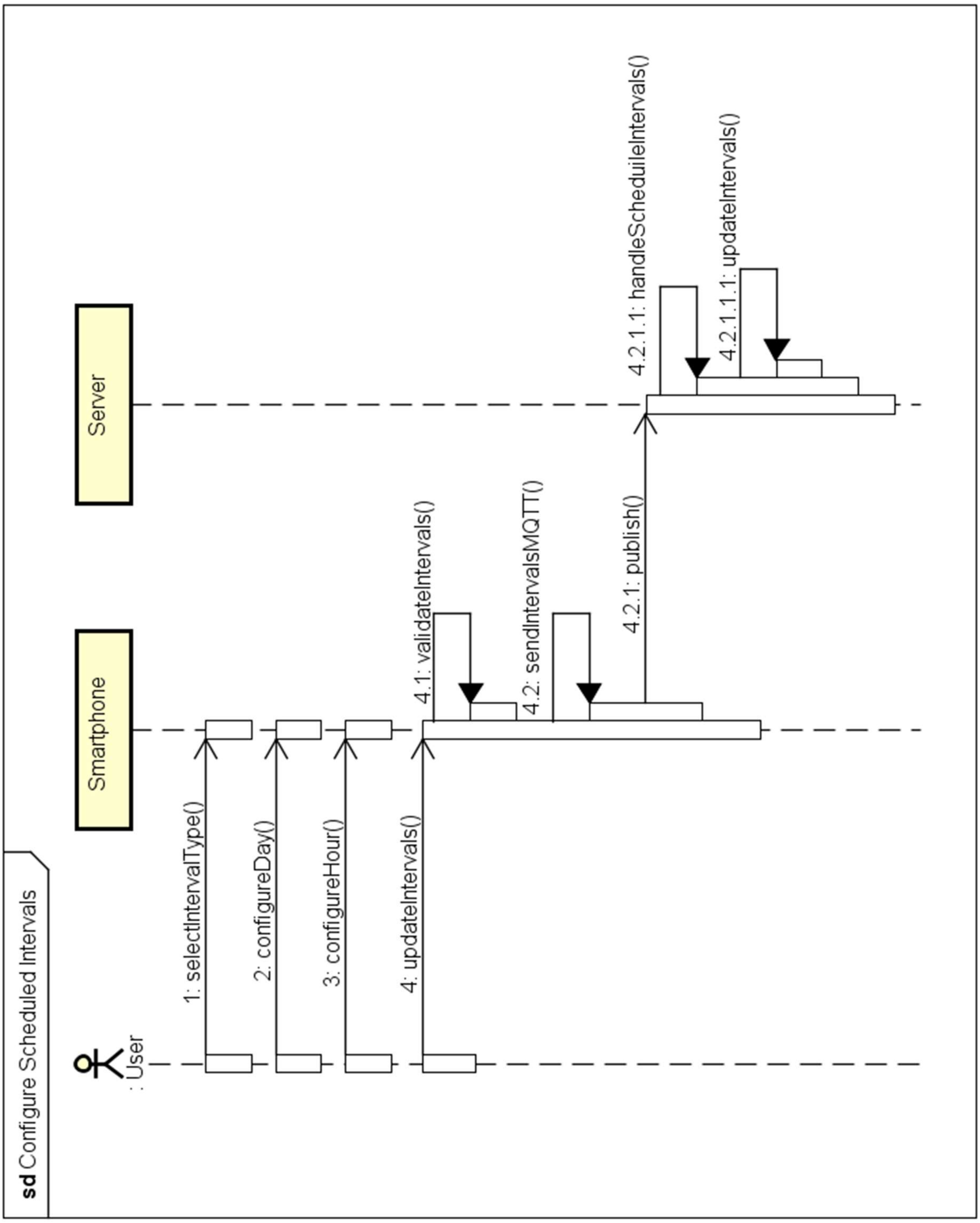

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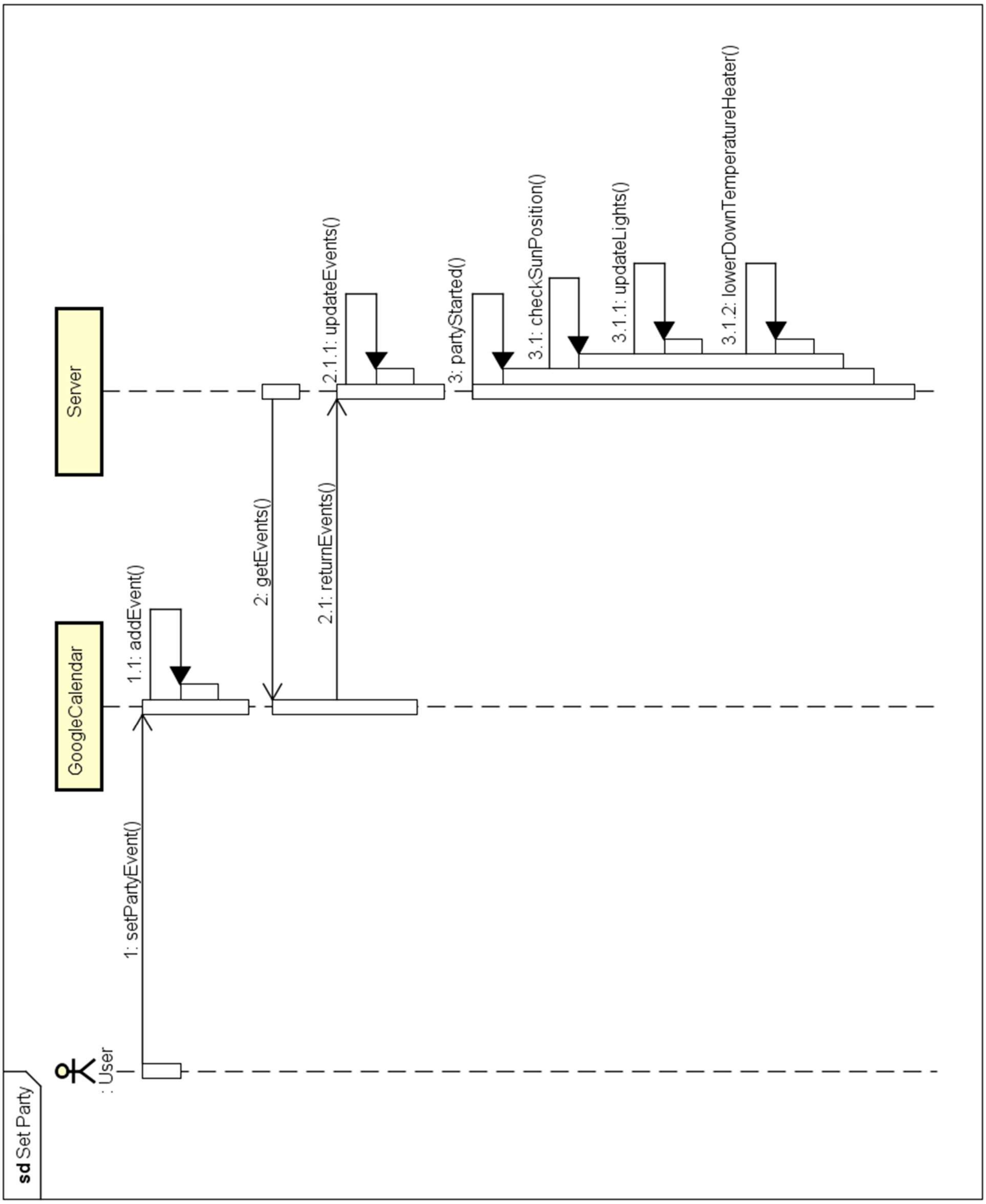

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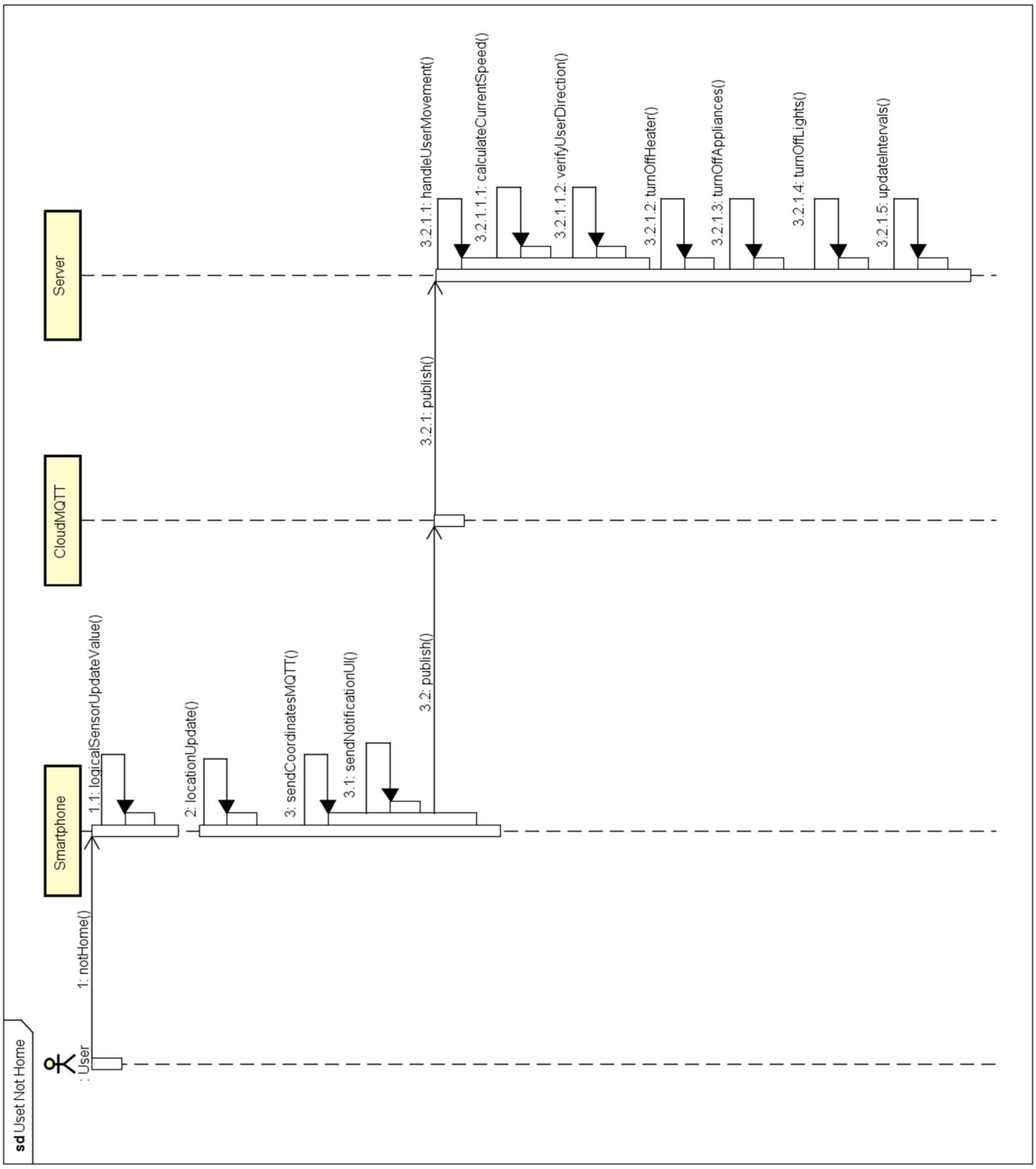

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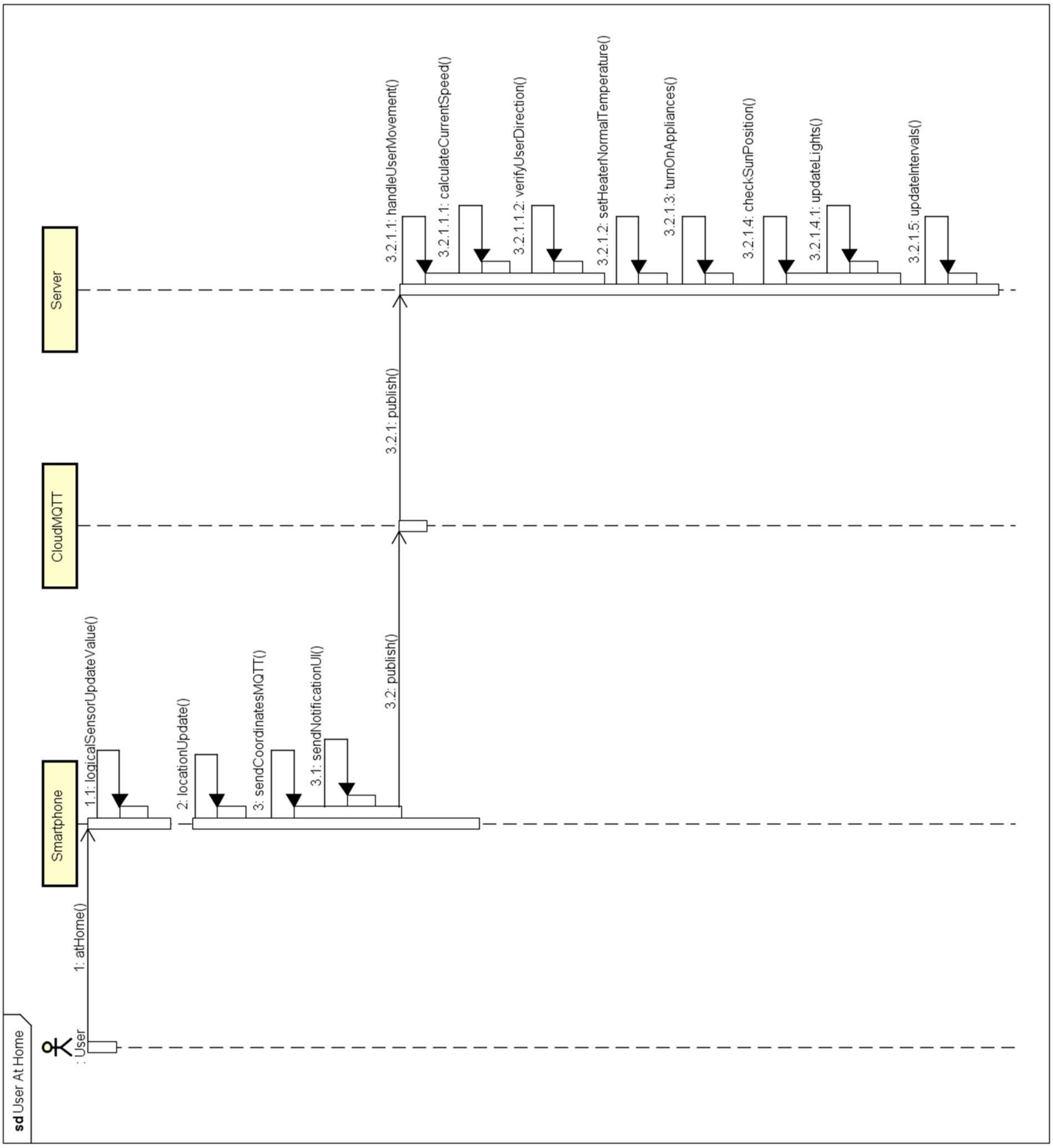

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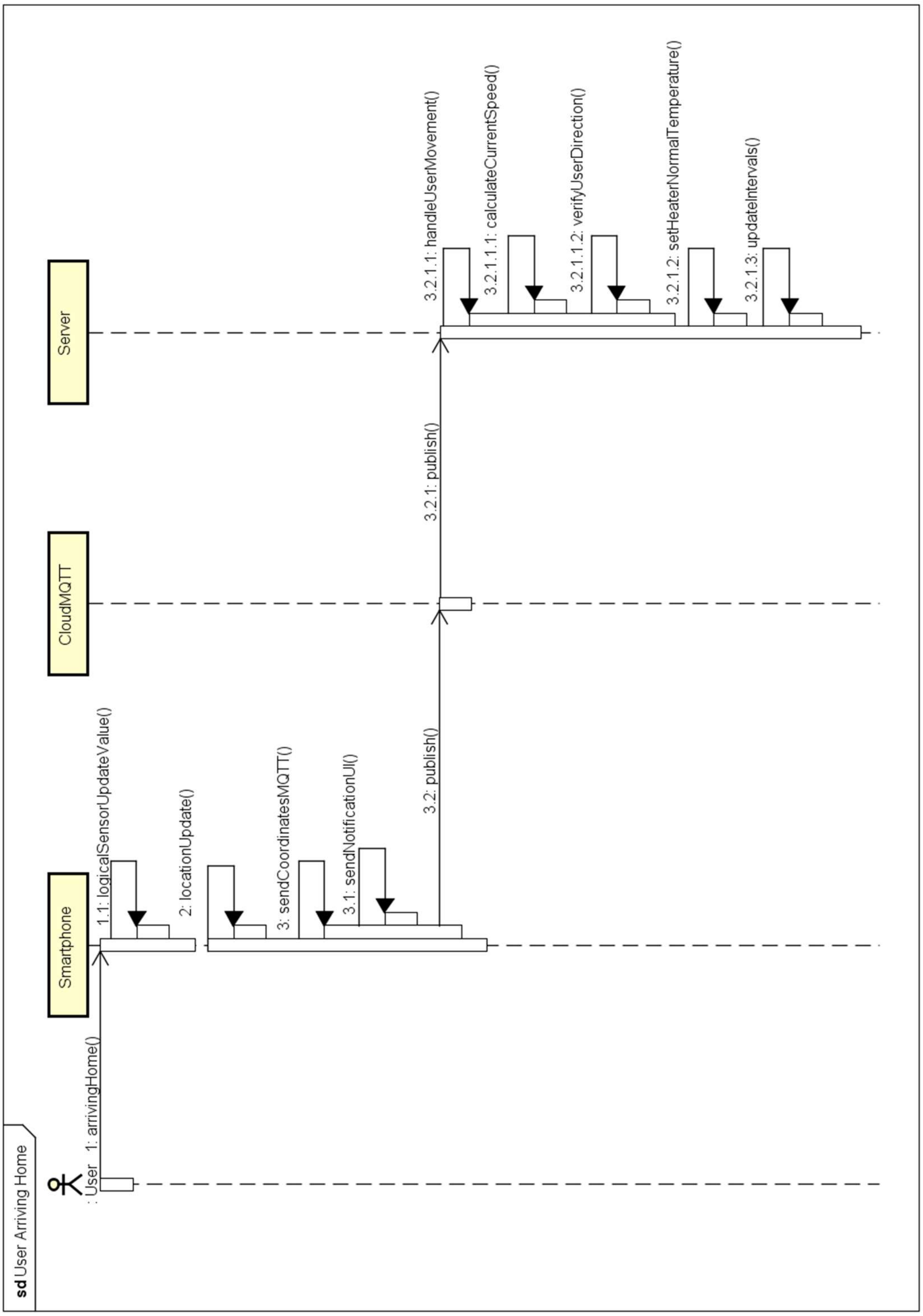

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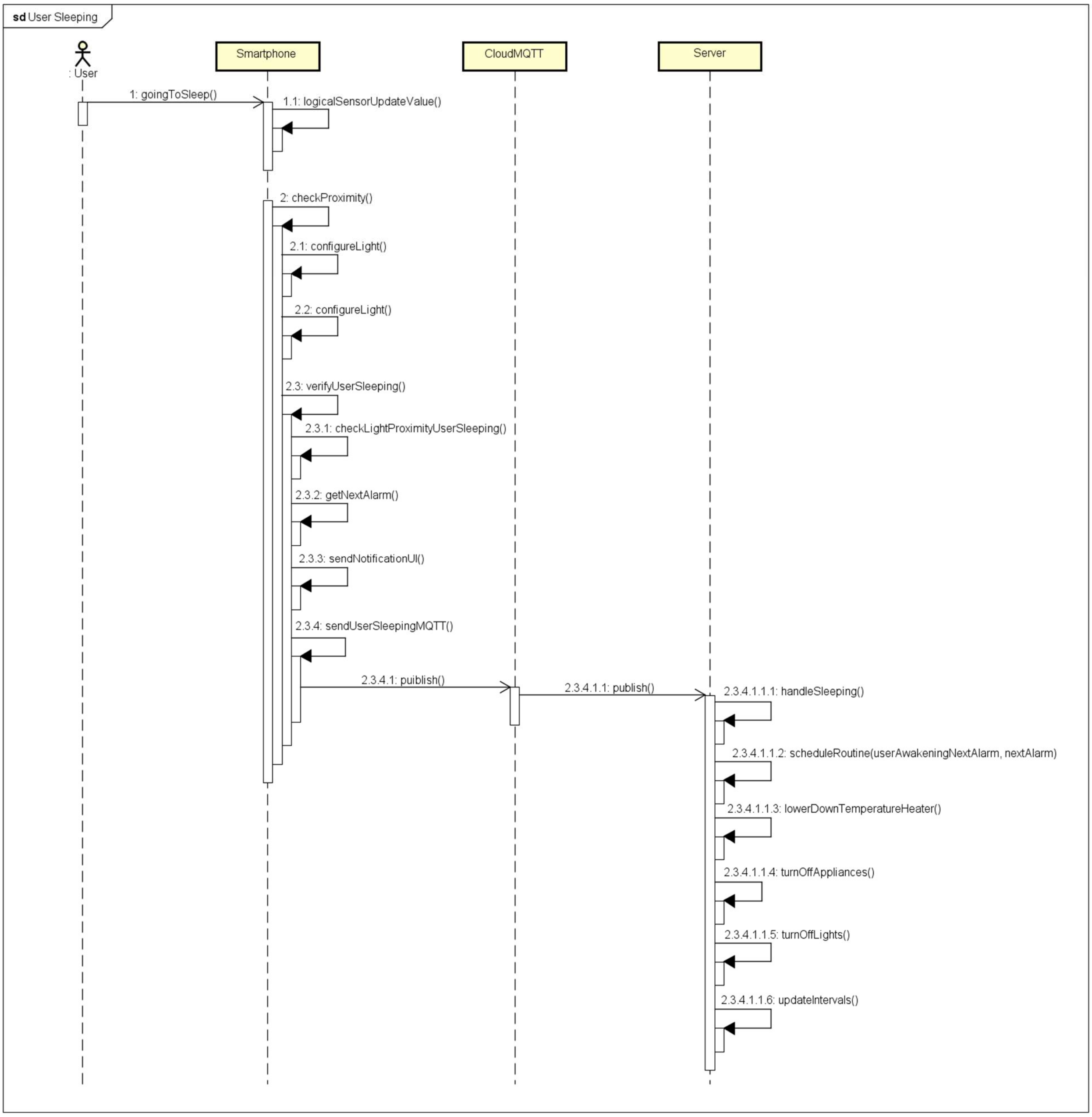

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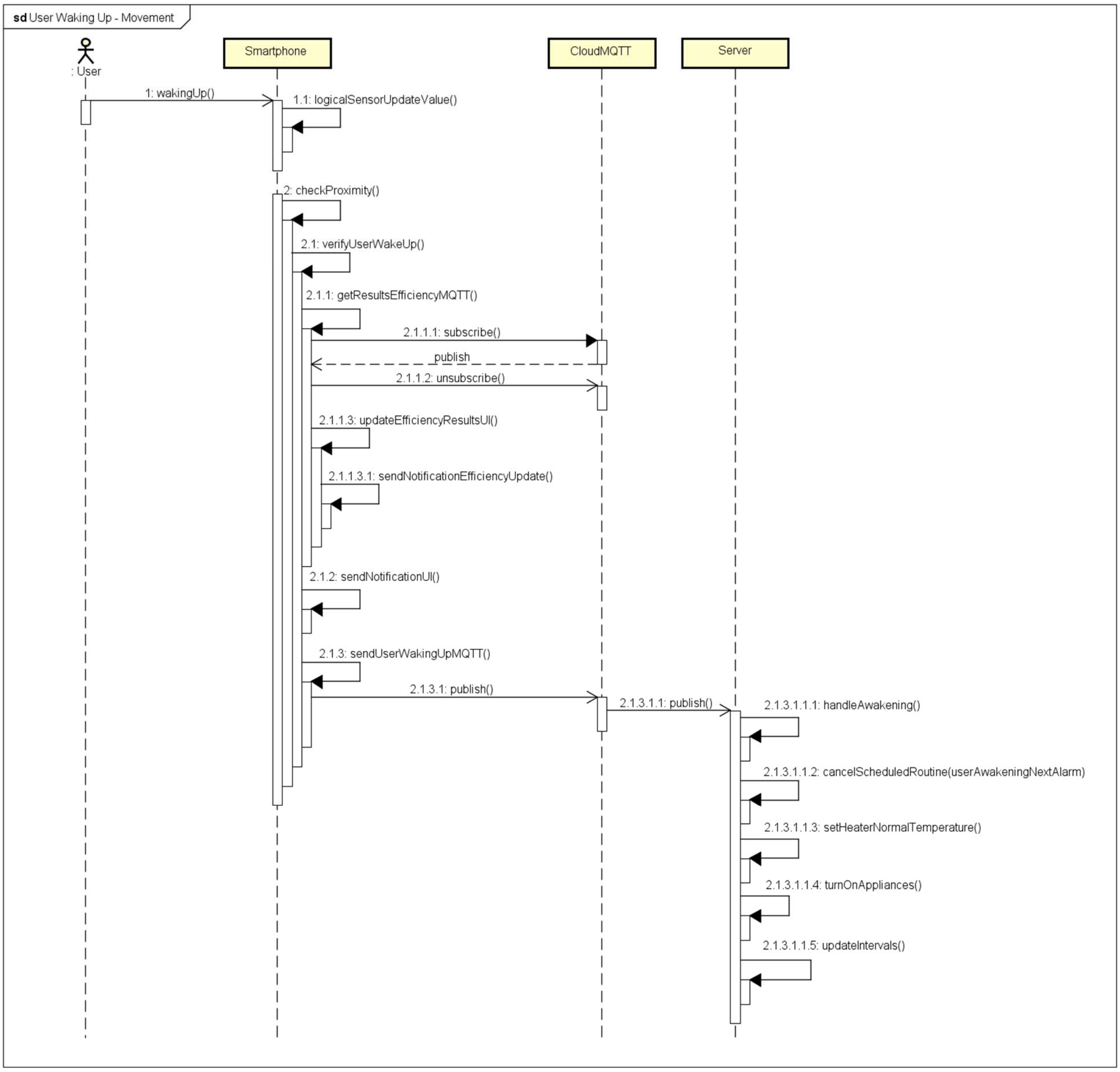
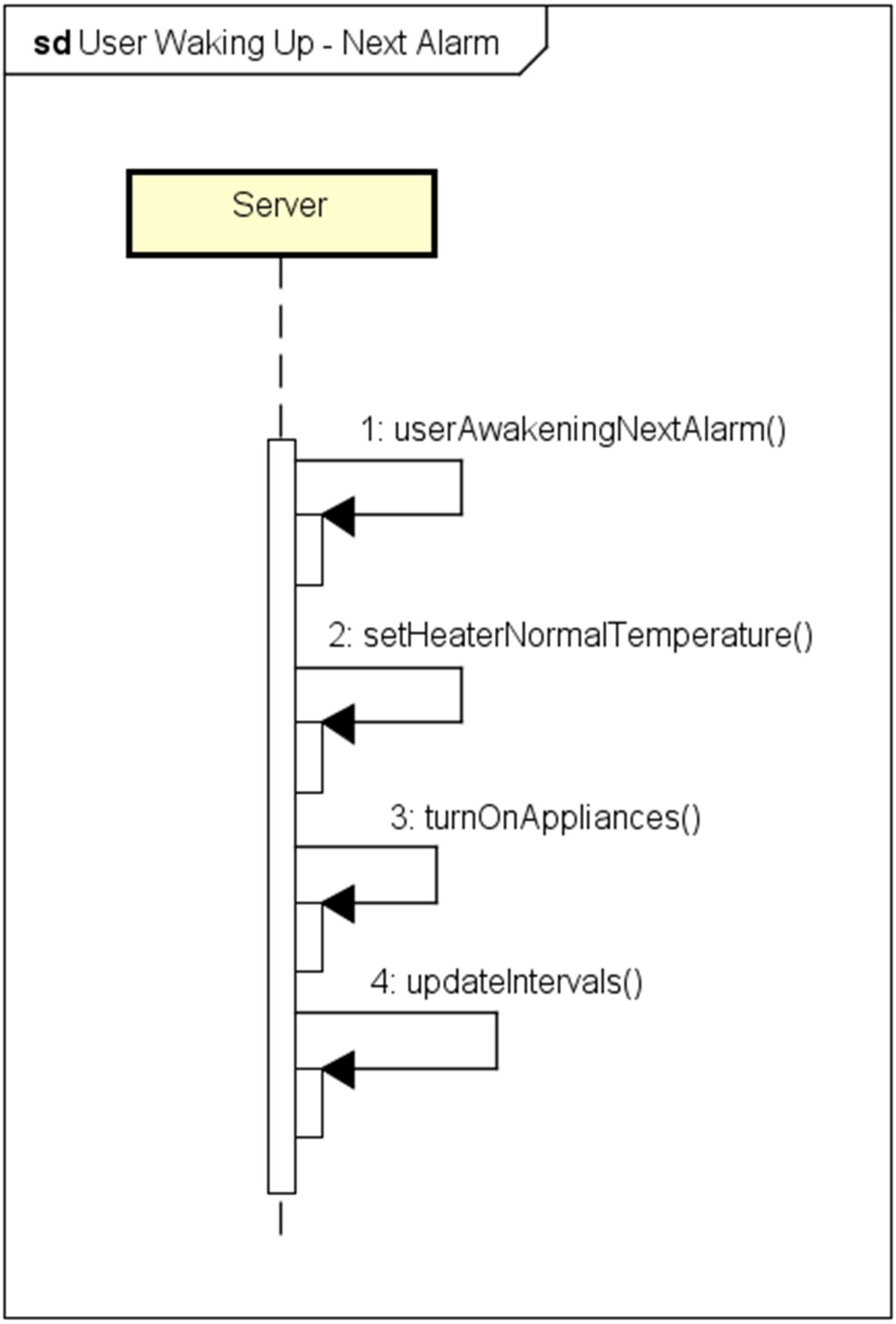

sd User Waking Up - Movement
: User
Smartphone
CloudMQTT
Server
1: wakingUp()
1.1: logicalSensorUpdateValue()
2: checkProximity()
2.1: verifyUserWakeUp()
2.1.1: getResultsEfficiencyMQTT()
2.1.1.1: subscribe()
publish
2.1.1.2: unsubscribe()
2.1.1.3: updateEfficiencyResultsUI()
2.1.1.3.1: sendNotificationEfficiencyUpdate()
2.1.2: sendNotificationUI()
2.1.3: sendUserWakingUpMQTT()
2.1.3.1: publish()
2.1.3.1.1: publish()
2.1.3.1.1.1: handleAwakening()
2.1.3.1.1.2: cancelScheduledRoutine(userAwakeningNextAlarm)
2.1.3.1.1.3: setHeaterNormalTemperature()
2.1.3.1.1.4: turnOnAppliances()
2.1.3.1.1.5: updateIntervals()

(continues)

APPENDIX 1. (continues)



(continues)

APPENDIX 1. (continues)