GreenMind - An Architecture and Realization for Energy Smart Buildings

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Abstract—Sustainability and energy-efficiency are receiving increasing attention. Existing buildings are responsible for more than 40% of the world’s total primary energy consumption. Current building management systems fail to reduce unnecessary energy consumption and preserve user comfort at the same time. We propose a software architecture for energy smart buildings that includes a set of concrete software solutions that tackle energy consumption sub-systems; i.e., heating, ventilation and air conditioning (HVAC), lighting, workstations and other appliances sub-systems. The primary goal is to save energy while preserving user comfort. Experimental results showed that our proposed solutions are able to save up to 56% of electricity used for lighting, at least 20% of electricity used for heating while saving from controlling workstation as well as other appliances are 33% and 10%, respectively.

I. INTRODUCTION AND MOTIVATION

Today, a simple web search of terms “sustainability” and “energy-efficiency” gives between 38 and 122 million results. Institutions worldwide, such as the European Union (EU), have goals for a 20% cut in Europe’s annual primary energy consumption by 2020. Existing buildings are responsible for more than 40% of the world’s total primary energy consumption [24]. Enterprise buildings are responsible for a significant fraction of the energy consumption and greenhouse gas emissions worldwide [13].

To tackle this issue in Europe, the European Commission proposed several measures to increase efficiency at all stages of the energy chain: from generation to final consumption. The EU’s measures focus on the building sectors where the potential for savings is one of the greatest.

However, on 28 June 2013, the European Commission published a report on progress by member States towards Nearly Zero-Energy Buildings (NZEB), which are to become the norm for all new buildings in the EU by the end of 2020. The conclusion of the report is that too little progress has been made by the Member States in their preparations towards NZEBs by 2020 and that Member States have to significantly step up their efforts to implement the requirements regarding NZEBs.

Building management systems are a computer-based control systems installed in buildings that control and monitor the building’s mechanical and electrical equipment. Systems linked to a BMS typically represent 40% of a building’s energy usage; if lighting is included, this number approaches 70%. BMS systems are a critical component to managing energy demand. Improperly configured BMS systems are believed to account for 20% of building energy usage [15], [30].

We consider that the current building management systems fail to reduce unnecessary energy consumption and preserve user comfort at the same time because they are unable to cope with changes caused by the user’s interaction with the environment. To cope with this dynamicity, we propose a software architecture for energy smart buildings as well as a set of concrete software solutions that tackle separate building sub-systems. We sense the environment using existing equipment where possible (e.g., we use PCs/workstations to detect user activity and presence), new sensors where existing equipment is not sufficient (e.g., PIR sensors to detect movement and user presence), and then make energy-saving decisions using gathered sensor data. Finally, we trigger actuators to cut unnecessary energy consumption whenever and wherever possible, for instance, turn off the workstations when not being used and lights when presence is not detected or natural light is sufficient.

We were awarded a Green Mind Award of the University of Groningen, which enabled us to implement our proposed solutions to a real building (the Bernoulli building) [4]. This provided a validation and a test-bed for our approach. The experimental results show that our proposed solution is able to save significant amount of energy whilst preserving user comfort. More specifically, our proposed solutions save up to 56% of electricity used for lighting, at least 20% of electricity used for heating, 33% saving from workstation consumption, and 10% of electricity used for other appliances.

This paper is organized as follows. In Section II, we explain our vision using a motivating use scenario. In Section III, we propose a general architecture for energy smart buildings. In Section IV, we present our prototype implementation and describe the pilot project. In Section V, we discuss the related work, and finally, in Section VI, we state our conclusions.

II. A WORKING DAY IN AN ENERGY SMART BUILDING

It is the first working day after a long vacation for John, a user of our smart energy building. As John is approaching the building with his bicycle, a sensor at the entrance detects his presence from his office key card. That triggers the heating system to warm up his office to a preferred room temperature

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and ventilation system to pump in the fresh air. After few minutes, while John is using stairs to come to his office, his PC is also starting.

At the moment he approaches his office door, a sensor detects his presence, unlocks the door and turns on the lights. From a room speaker, John hears a pleasant welcoming voice of his virtual secretary: "Good morning, John! It is 9AM and your room is prepared for you. Room temperature is 20 degrees and your PC is on". While John is hanging his jacket and taking his items out of his bag, he hears more information about his schedule, missed phone calls and important emails to be answered. Besides that, he is also being informed about total energy saving while being on vacation and about new energy saving goals of his department. As he wants to start with his work, he interrupts his virtual secretary by saying: "Thank you, Miranda! That would be all for now".

At 11AM, John’s colleague knocks his door and enters to give John an update about project developments while he was away. John starts speaking with his colleague and after 3 minutes of inactivity his PC goes to the sleep mode. As he was about to show some vacation photos to his colleague, he gets slightly annoyed by PC sleep action and wakes up the PC by touching the keyboard right away. That directly changes his PC sleep timeout from 3 to 5 minutes.

Now, it is 1PM and John leaves his office for a lunch. The room sensors detect his absence and turn off heating & ventilation and put his PC to sleep mode. Now, for one hour John does not consume any energy in his office. As John arrives first to the building restaurant, lights go on only in the area where he sits, while other lights in neighboring areas are dimmed. While he is enjoying lunch with his colleagues, he notices that lights above them also get dimmed as the natural light increases. As soon as he is finished with his lunch, he passes occupancy detection sensor at the staircase and the room preparation actions are triggered again. Only this time after entering his office, the lights do not turn on. The reason for that is a light sensor detected enough sun light coming from outside. Also, heating did not start 10 minutes before entering the office, but only 3 minutes before. The reason for that is because both outside and inside temperature sensors have detected a significant increase in temperature, caused by very warm and sunny weather. This results in energy saving and John is informed about that by his virtual secretary. Motivated by that, to contribute to the saving goal of his department, John decides to cool himself down and asks his virtual secretary: "Miranda, please decrease heating for 20%. Thanks".

At 5.45PM, John finishes with his work and leaves his office in a rush to get on time to his dinning place. Sensors detect his absence and turn off all energy consuming devices immediately. John’s office again becomes energy neutral until the next working day.

III. THE GREENMIND ARCHITECTURE

Energy and sustainability are the focus points in teaching and research of the Groningen university [11]. This research is conducted as part of multiple research projects at the Distributed Systems research group at the University of Groningen. With our research, we aim to save at least 7% of annual electricity consumption of the Bernouli building [1] through automatically controlling heating, ventilation, and air condition (HVAC) systems, lights, appliances, and by providing energy consumption tracking.

The Bernoulli building is a new building of the University of Groningen. It is located at the Zernike Complex (Nijenborgh 9, Groningen, The Netherlands). The building has floor area of 12,000 square meters accommodating 180 offices, 16 lecture rooms, 8 meeting rooms, and 6 social corners for more than 300 of staff members and capacity for more than 500 students. It’s annual electricity consumption is between 1,350,000 kWh and 1,400,000 kWh (for 2011 it was 1,396,276 kWh, while for 2012 it was 1,359,821 kWh).

In order to reach the proposed minimal electricity consumption saving of 7%, a system should be able to alter the state of devices such that energy can be saved without the loss of comfort or drastic alterations to the building’s structure. Two saving goals are set in order to judge the effectiveness of proposed solutions.

- Lighting: the energy consumption of lighting should be lowered by 25%. Lighting is currently motion enabled or always on, which is not very efficient.
- HVAC: the energy consumption of heating and ventilation system should be lowered by 20%. Radiators inside each room can be controlled individually, thus they turned on just long enough in advance in order to prepare the room when users really use their rooms.
- Workstation: the energy consumption of workstation should be cut by 25%. Sleep time out of each workstation should be adjusted to the minimum as possible, preserving user comfort while saving as much energy as possible.
- Plug loads: the energy consumption of electronic devices should be lowered by 10%. Non-essential devices sometimes remain enabled unnecessarily (e.g., during absence, night, or weekend).

In order to satisfy the use scenarios of an energy smart building and the above mentioned saving policies in particular, we propose an architecture that takes, as its inputs, into account (1) user activities, such as working with PC, being present, absence, (2) appliance statuses, e.g., PCs are idle for a certain amount of time, and (3) environment information (natural light intensity, outdoor temperature, etc.), and accordingly adjust the environment to preserve user comfort and to save energy at the same time. The proposed architecture goes from the physical level of consumption measurement, live environment monitoring, up to Hierarchical Task Network (HTN) based controlling. Furthermore, the system also provides displays that bring consumption information at the building level, but also at the personal level.

A. Design Principles and Overall Architecture

In order to reach the envisioned goals, an automated system should be able to influence the energy consumption of lights and electronic devices in the existing offices. The system also needs to collect the consumption information of the individual devices and provide this information to users in meaningful ways, thus creating user awareness about energy savings.
The governing of such system itself consists of multiple subcomponents. Components work together to reach their common goal, reducing the energy consumption in the offices while preserving user comfort, sharing useful information with the other components so that both the raw sensor data and other processed information is accessible to each component. To make the management of these components easier, the components communicate either through a REST interface or a message queue, which allows for loose coupling between the components. REST is the dominant web application programming interface (API) that is usually described in the context of HTTP, whereas message queues are separate software components that can be used for asynchronous communication.

It is envisioned that over time new sensors and actuators are added to the system, as well as new components that provide better or completely new functionality, so that the system keeps updating and improving. Through the loose coupling of the individual components the system should scale better, more easily adapt to new components, and be easier to manage than a conventional BMS. By using a dynamic combination of small hardware, that integrates with the existing building design, and dedicated software the system has the potential to save energy at a relatively low cost without the loss of comfort and even the potential to increase comfort. The system is named the Green Mind system which refers to its origin as a proposal for the Green Mind Award.

The overall architecture is shown in Figure 1. At the bottom lays the Physical layer that contains all devices connected to Sensor and Actuator Gateways (SAGW) above. The Physical layer also includes Sleepy, a software agent that runs on clients, i.e., workstations, working as sensor and actuator specifically for monitoring and controlling workstations. The data processed by SAGW is very important for the Context component to reason and provide a complete and consistent view of the environment. This essential view is stored in a Central Database together with consumption data from the Consumption Measurement component. Also, the crucial view about the environment is provided to the Controller that makes decisions how to control lamps, workstations, appliances. The control decisions made by the controller are sent to the Orchestrator that translates them into proper commands distributed to either SAGW or an Sleep Management Solution - SMS component that takes care of controlling workstations through interacting with the Sleepy software agent. In upper right part of the architecture one can find the Dashboard/Mobile App component that is responsible for delivering in a very meaningful way the consumption information to each and every occupant of the building.

B. Physical Layer and Gateways

At the Physical Layer, wireless sensor networks (WSNs) provide the basic infrastructure for gathering the raw contextual information from the environment. For example, light and temperature sensors gather information about ambient context while passive-infrared (PIR) and pressure sensors or electricity measuring plugs can report the situations of the monitored phenomena and devices. Also, electric devices are controlled by using actuators that can perform actions based on commands made by the controller.

1) Gateway: The environment can only be understood through information gathered by sensors. The more sensors are deployed the more precise information can be gathered. The diversity of sensors implies that the system should be able to address the heterogeneity of WSNs. Thus, the Gateway is capable to read information from different networks and join data read from them into only one standardized message with a specific format, realizing the first step of data processing. In addition, the Gateway encapsulates the complexity of WSNs and makes components independent from each other.

2) Interface to Upper Components: We benefit from the use of a message broker to reduce coupling between low-level components (i.e., WSNs and Gateway) and the high-level one (i.e., Context), which makes indeed possible for the components to run independently in a distributed manner.

C. Context Component

The Context takes as its input the sensor data processed by the Gateway. The Context component has two subcomponents: (1) ambient context and (2) activity recognition. The ambient context takes care of other ambient information, such as natural light intensity. Furthermore, we employ context consistency diagrams (CCD) [19] as a key component for fault correction. A CCD is a data structure that provides a mechanism for probabilistic reasoning about the current situation and determines the most probable current situation in the presence of inconsistencies, conflicts, and ambiguities in sensor readings. With reliable context information provided by CCD, for user activity recognition, we apply an ontology-based activity recognition approach to derive high-level activities from data from simple sensors. Our ontology-based activity recognition solution is represented in [29]. For more detail about the inside implementation of our context component, one should refer to [28].

D. Fine-Grain Energy Consumption Measurement

We measure consumption at the device level, i.e., electricity consumption by the occupant. Besides occupant devices, we also measure light consumption. That way we know total consumption per user. This enable keeping of the user consumption history, as well to give user a feedback on the consumption. Even though the Consumption Measurement (CM) component works closely together with the SAGW to retrieve the consumption measurement data, it is not part of the SAGW. Retrieved data needs to be correctly stored in the database, and old or missing history log entries also need to be retrieved. This data management is not part of the SAGW and thus are the energy consumption measurements handled by the Consumption Measurement component.

E. Ontology-Based Database

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

F. HTN-based Controller

The components belonging to the composition level are the high level components. These components use all the available data and functionality from the lower layers in order to make calculated decisions about the desired state of devices. This is also the layer where the system management components are located. The controller is the component responsible for providing the system with the ability to automate the sensor and actuator behavior, which can possibly influence the energy consumption. We propose an approach that manipulates context information, and combines an ontology-based technique to recognize occupant activities with Artificial Intelligence (AI) planning to automatically produce office adaptations at run-time. The proposed approach is initially described in [23].

Basically, given the context information and the recognized activities, a technique based on Hierarchical Task Network (HTN) planning is adopted to compose a plan, that is, a sequence of device operations. Then, plans are executed by using a wireless network of actuators. Our HTN planner takes care of controlling HVAC and lighting systems, but also it invokes the Computer Sleep Management (CSM) component for controlling workstations in order to reduce energy consumption while still preserving the user comfort at the same level.

G. Computer Sleep Management

The goal of Computer Sleep Management (CSM) solution is to minimize the energy usage of workstations (e.g., PCs). The way CSM achieves this goal is by taking control of the process for putting a PC into sleep mode. By doing this it is able to put workstations to sleep when no activity is detected and provide the administrators with important information with regards to the activity history of a workstation and whether a workstation should be sleeping or not. Besides this, using CSM Dashboard GUI we can see the activity of a user and put workstations to sleep, wake it up, turn it on or off.

The architecture consists of the following components: (1) Sleepy Client, a client monitoring power management events and workstation activity while listening to and executing commands from the server; and (2) Sleep Management Server, a server managing data received from clients and listening to requests from other components, forwarding these requests to the clients.

The activity is defined as the mouse and keyboard activity in the past $X$ minutes (a configurable parameter). If there has been keyboard and mouse activity in the past $X$ minutes, then the workstation is considered to be “active”. If there...
has not been any activity in the past X minutes, then the workstation is considered to be "idle". This information is sent every Y minutes (also a configurable parameter) to the Sleep Management Server, which finally stores the data in the database. More technical details on CSM solution are described in an internship report [31].

H. System Operation

The typical operation cycle is as follows: 1) the SAGW and SMS send messages to the context based on the changed values from their sensors and actuators, 2) the context component processes these messages to create new variables and sends the variables to the controller component, 3) the controller executes HTN planning based on the received variables, 4) messages that require action taken are then sent from the controller to the orchestrator, 5) the orchestrator then sends commands to either the SMS or SAGW, depending on the received message, 6) the SMS or SAGW then executes the requested action (e.g., turn off a device or put a workstation to the sleep mode), and then the cycle repeats. The components do not wait until a full cycle is completed (e.g., a change in the sensor value can occur at any moment).

I. Display

To raise awareness and decrease energy consumption as much as possible it is important to take users into the loop. The GreenMind system is able to provide the personal energy consumption information to each user in a very meaningful way, thus motivating users to save energy consumed by their appliance. The graphs are presented with different level of granularity, more specifically: in daily, weekly and monthly view. GreenMind provides mobile application as well as web-based interface with which users are able to keep track of consumed energy, to set saving goal for a certain period (e.g., week, month), to participate in saving campaigns managed by building managers, etc.

J. Orchestrator

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

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

K. System Communication

The message queue can be used by the components of the system to communicate with each other, with or without knowing the physical location of other components. Message queues can significantly simplify the implementation of the separate components and also improve performance, scalability and reliability. Another advantage of using a message queue is that the sender and receiver do not need to communicate with the message queue at the same time as the messages are stored onto the queue until the recipient receives the message. As a result, the communication between different components is asynchronous.

IV. Prototype Implementation and Pilot Project

A. The GreenMind Prototype Implementation

We realized a prototype implementation and deployed it in a pilot project in our own building at the University of Groningen, that is Bernoulli building. The Bernoulli building, which has 10500 square meters gross floor area with the size of 33 by 83 meters and a height of 27 metres, is a new building of the University of Groningen. It can accommodate 350 staff members and 500 students. In the prototype, we implement a gateway that can handle a wireless network of simple sensors and a wireless network of electricity measuring plugs, providing just enough ability to monitor necessary environmental information as well as the ability control lighting system. Also, we consider the Sleepy agent as another type of sensor and actuator that can monitor the activity of computers and can control their sleep mode at the same time. The first version of BackOffice, Display, and Mobile application are released, together with a complete implementation of HTN-based controller, rule-based context component. All make it a complete total solution at its first stage.

1) Physical Layer and Gateway: We use IEEE 802.15.4 compliant wireless TelosB-based sensors produced by Advantive Systems [2]. The sensors are equipped with ultra low-power 16-bit microcontroller MSP430 and run a low-power consumption management algorithm. The motes also have an extension interface that can be used to connect various sensor boards containing photo, temperature, humidity, pressure sensors, and accelerometers, magnetometers and microphones. The on-board PIR is used together with light sensor. The motes are programmed in nesC and run on the TinyOS 2.1.1 embedded operating systems. For electricity measuring plugs, we use Plugwise [8] products consisting of plug-in adapters that fit between a device and the power socket. The adapters can turn the plugged device on and off, and can, at the same time, measure the power consumption of the device attached. The plugs form a wireless ZigBee mesh network around a coordinator. The network communicates with the base station through a link provided by a USB stick device. We implement the Gateway as a process running in the background that reports power state of controlled devices. It is written in Java.

2) Interface to Upper Components: The RabbitMQ [32] messaging framework is chosen as it is a complete and highly reliable enterprise messaging system based on the emerging AMQP [3] standard and runs on all major operating systems.
3) **Consumption Measurement component:** The Consumption Measurement (CM) component gathers data from sensor and actuator gateway (SAGW) and stores it in the database (OrientDB). The CM is written in Java. It uses the history buffer to limit the network traffic and processing load. By requesting all history logs until the last log that was stored it is not an issue if the CM fails. The Plugwise devices will continue to monitor the energy consumption and when the CM restarts it will simply gather all the missing data. The same also applies when the network of the Plugwise devices is temporarily unreachable. When the network connection is reestablished the consumption component will retrieve all data until the last stored history log.

4) **Context:** The ontologies are developed using Protégé [9], a graphical tool for ontology development that simplifies design and testing. Ontological reasoning is performed using the HermiT [6] inference engine, and its application programming interfaces (APIs) for the Java programming language. The recognition algorithm is developed in Java and implemented as an on-line recognition system. More details are presented in [29].

5) **Graph Database:** OrientDB is an open source database with features from both document and graph database systems.

OrientDB excels in scalability, availability, performance and price. After careful consideration, OrientDB is picked as the main storage facilitator for the whole GreenMind system.

6) **Computer Sleep Management:** The main responsibilities of the Lazy Sleep are monitoring the activity on workstations, and remotely controlling workstations in order to increase the energy efficiency within a building. One of the ways Lazy Sleep achieve this is by putting workstations to sleep when they are not in use. Lazy Sleep also provides ways of centrally configuring options for workstations in order to decrease their power consumption. Sleepy client is written in C#.NET, the other components at the server side are written in Java.

At the moment, the Lazy Sleep supports the following Windows versions: Windows XP and Windows 7. Current development focus is on features for Windows 7 as that is an operating system that is most widely used at the University of Groningen and also supported by its IT services. The Sleepy runs on workstations and is responsible for monitoring the activity on a workstation. An activity is defined as keyboard and mouse movement. Sleepy is also responsible for changing the sleep timeout (time before a workstation enters sleep mode after being idle/inactive for that specified amount of time), as well as executing "turn off" and "go to sleep" commands received from the Sleep Management Server.

The Sleep Management Server is responsible for collecting data from Sleepy clients and publishing this data on RabbitMQ. Furthermore it is also responsible to forwarding commands for Sleepy clients to the correct Sleepy client by mapping MAC addresses to IP addresses.

The Sleep Data Concentrator is responsible for consuming data from Kafka and storing this data in the database in a specified format. For more detail about the implementation of the Lazy Sleep, one should refer to [31].

7) **HTN-based Controller:** All components of the Planning System are implemented completely in Scala programming language. The problem converter translates the context information and activities described in JavaScript Object Notation (JSON) syntax into Hierarchical Planning Definition Language (HPDL) syntax [21]. The domain modeller enables creating models based on the BNF form of HPDL as well. Consequently, the planner’s input consists of HPDL domain and problem descriptions. Planning is offered as a service by implementing its functionalities as Representational State Transfer (REST) resources. Upon receiving a request with appropriate arguments, SH searches for a solution, structures the resulting plan in JSON, Extensible Markup Language (XML) or plain-text format, and returns it to the interested party.

8) **System Communication:** All the components in the Green Mind system communicate with each other through the use of JSON objects. JSON was picked because of the good readability, simple syntax and ease of use. JSON is also less verbose than alternatives like XML, which decreases the size of the message payloads. Developers of components that communicate with each other dictate the content of the messages that are communicated with each other. Depending on the data that the component requires, the body of the JSON object may change. For the sake of traceability with asynchronous communication and readability and consistency in generic messages, a basic template was specified to which all the messages of components should adhere.

B. Pilot Project Description and Setup

The pilot project is set at the Bernoulli building of the Faculty of Mathematics and Natural Sciences of the University of Groningen, The Netherlands. In this pilot project, six energy saving solutions were developed and tested, including:

1) **Consumption measurement lab**, 2) **Consumption display**, 3) **Computer sleep solution**, 4) **Lighting control**, 5) **HVAC control**, and 6) **Plug loads control**. In this section, we firstly give more details on the deployment of each solution within our pilot project. We then provide the setup of the experiments that we use to evaluate our proposed solution and the experimental results, especially in terms of energy saving.

1) **Consumption Measurement Lab:** In order better to understand individual energy consumption and its patterns, we deployed electricity measurement devices in 12 different areas at the 5th floor of the Bernoulli building. Layout of the consumption measurement lab is illustrated in Figure 2. The areas that are measured by the system include eight offices, two hallways, one kitchen area, and one meeting area. Over a course of six weeks, from mid-May to late July, 2013 the office environment on the fifth floor of the Bernoulli building has been monitored 24 hours a day and 7 days a week.

The kitchen area is a common social area where office workers mostly meet during lunch breaks to use the microwave or to get their food from the fridge. The meeting area is a designated office for holding discussions and presentations. The meeting area does not contain any equipment except for a projector. Offices are the most common areas and differ in size, shape, interior and occupancy throughout the building. Despite the different design the general usage remains the same and thus the following can be controlled inside an office: 1) computers and appliances, and 2) lighting fixture.
Hallways are the common entrance halls that run between the different areas. The hallways allow entrance to the offices, kitchen area and meeting area that are measured by the system.

Measurements are divided into two segments. The first segment consists of the devices located in the offices. These devices and their consumption depend on occupancy of the offices and the usage of the devices by the staff that is located in that specific office. The second segment consists of the devices that are common goods. These devices are used by multiple people and mostly remain active throughout the day, even without people being present.

The information from Consumption Measurement lab was used to develop back-office software component which serves to model building spacial data and to assign particular measurement devices to employees, employees to rooms, etc.

2) Consumption Display: In order to understand pattern of electricity consumption at the level of the building as a whole, we have developed consumption display and deployed it at the Computer Science social corner at the 5th floor of the Bernoulli building, Figure 3.

The information on the display consists of daily, weekly and monthly view of consumption, together with moving average line. In order to show this information on the display, we had to use external hardware component to convert analogue pulse signal from the main electricity meter to a digital signal and to store it in a database before being able to show it graphically.

3) Computer Sleep solution: In order to understand the patterns of workstation usage, sleep timeout preferences and part of consumption coming from workstations, we have deployed Computer Sleep solution to 10 workstations at the 5th floor of the Bernoulli building. Per monitored workstation we show the activity (working or idle) and status (off, on, sleep). Besides that, we have ability to control the workstations using 4 actions: (a) send to sleep, wake up, turn off, and turn on. The activity and status of workstations are shown on a dashboard, see Figure 4. Also, control options can be used via the dashboard. Historical data is also stored in our database and it can serve to determine user consumption using workstation usage time and average workstation energy consumption values. Through database, we can generate many meaningful reports which may serve to motivate further energy preservation.

4) Lighting control: Lighting control system is deployed in the Restaurant on the ground floor of the Bernoulli building. There, we attached sensor/actuators to each individual lamp (30 in total), see Figure 5. That way, we can both measure the consumption as well as control each individual lamp or a group of lamps. Besides that, we also deployed motion and light sensors which give the input to the controller component to decide when lights do not necessarily need to be used (i.e. when no one is present in a particular area or when natural light provides satisfying high level of light). Using this system, we reduce electricity consumption by using lights only when they are absolutely necessary.
5) Heating and ventilation (HVAC) control: The goal of HVAC control solution was to reduce electricity consumption of HVAC system by reducing heating and ventilation time for room preparation to minimal required. The experimental results show that very high savings can be achieved.

HVAC control solution is tested in separate premises, outside the University of Groningen. The reason for that is because we needed to test this solution in an environment that is highly controllable. Experiments and results of our proposed HVAC control is represented in Section IV-C. Control of the HVAC system was done under assumption that heating and ventilator can be separately controlled on the level of room. As that is not the case in the Bernoulli building, the experiments were performed on external location, at the medium size storage room nearby the city of Groningen, The Netherlands. The experiment was carried in one week, from Jan 27 to Feb 2, 2014. In this experiment, we used: a computer to run the prototype software, a heater with capacity of 2KW (for safety reason, the heater was set to perform at 25% of its full capacity), a Meteo sensor that can measure humidity, pressure and temperature of the environment, a Plugwise device to control the heater. The setup of our experiment is shown in Figure 6.

![HVAC experimental setup](Image)

**Fig. 6. HVAC experimental setup**

C. Energy Saving Evaluation

We run intensive experiments at our pilot project areas in order to evaluate our solution in terms of accuracy as well as scalability and, most importantly, in terms of energy saving.

1) Experimental Results: Regarding the accuracy and scalability of the solution, each and every proposed approach and component was intensively tested in our previous research, in which experiments were conducted at our living lab at the University of Groningen. Experimental results are discussed detailed in our previous publications. In particular, in [29], the experiments conducted show that in such experimental setup, our ontology-based activity recognition solution is able recognize six typical office activities (working at a desk with or without a PC, having a meeting, having a coffee break, and presence/absence) in three office activity areas (two working rooms and a coffee corner) for two persons with average accuracy over 88%. In [28] we evaluated the performance of CCD when applied to correct faults in sensor readings. Results show that CCD helps to significantly improve the accuracy of the context component, thus producing reliable context information from unreliable sensor data. The performance of the HNT-based controller is evaluated extensively in [23].

With respect to energy saving evaluation, in [22] we discuss the potential saving brought from plug load control with experiments conducted in two weeks. The results show that our solution saved 10% of electricity consumed by a set of appliances (a fridge, a laptop, a printer, a projector, a microwave, and a water boiler). Meanwhile, saving archived from controlling lighting and workstations was initially evaluated in [23], where we run experiments within two private offices of two users and determined how much electricity saved by controlling their two workstations and ceiling lamps within their offices. The overall solution shows intriguing potential for energy saving in the order of 70%, given mostly sunny days and a provisional set of devices for experimentation.

In general, the experimental results are very promising. Separate experiments conducted for each individual solution of ours show that by applying our solutions it is possible to archive significant savings from all four main subsystems (i.e., HVAC, lighting, workstations, and plug loads) within office buildings.

2) Energy Saving Potential: In the followings, we present analysis on energy saving that is very potentially achieved by using our GreenMind system. The current estimated annual values are calculated based upon the average energy consumption of the actual measured devices within and outside office hours during these six weeks, whereas the after estimated annual values are estimated only based on the possibilities of the GreenMind system to limit the energy consumption.

a) Potential Saving from Controlling Lighting System: Within Bernoulli building, a lamp fixture consumes around 75 watt when turned on. There are two or three fixtures inside each office. This means that the lighting of a single office consumes from 150 watt to 225 watt per hour for around eight hours. This equals to approximately 1200 watt to 1800 watt per day, that is simply being wasted on a sunny day. Currently, Passive Infrared (PIR) sensors are equipped to control lamps based on movement, however, PIR alone is not enough to save energy. According to a weather condition report from the Royal Netherlands Meteorological Institute [10], there is an average of 4.5 hours (56% of the eight hours of work time per office) of sunlight per day and 228 workdays per year, the annual savings could amount to 153.9 kWh to 227.81 kWh per office annually. Particularly, in an extreme case we evaluated in [23], the overall solution shows intriguing potential for energy saving in the order of 70%, given mostly sunny days and a provisional set of devices for experimentation.

b) Potential Saving from Controlling HVAC System: The experiment results show that the amount of time that the heater needed to warm up the storage differentiates everyday. The duration for preheating changed based on the initial temperature of the room, which is affected by the outside temperature. In the worst case, the heater needed to be turned on up to 80 minutes before the scheduled time in order to warm the storage house to 10 degrees Celsius. Yet, for some days the heater was just turned on approximately 18 minutes before the scheduled since it was a warm day. The difference between two above days is almost 60 minutes in using the heater, which results in energy saving.
One notable point here is that the temperature at the scheduled time varied of about 2 degrees Celsius. This variation can be the results from 2 causes, the first one is that the experimented storage house is not 100% wind isolated, thus this might affect the result. The second cause is that the U-Value for the materials of the storage house was estimated one. These factors contribute to the variation in the final temperature.

In either case, we found the experiment results very satisfying as the clear relation between outside weather and necessary heating start time was noted. Additionally, by applying machine learning algorithms on top of this solution, we could more precisely determine latest heating start time. Finally, depending from the schedule of the room, our experiments showed that electricity savings can be from 20% to 78% only on heating.

c) Potential Saving on Controlling Workstations: A standard university issued workstation consumes 120 watt when both computer and LCD screen are on. The consumption slightly decreases around 13:00 when staff member going out for lunch and manually turning off the monitor and/or computer for the duration of the lunch. Note that the workstation still consumes some energy outside office hours.

The estimation of an energy savings potential of 47% per regular workstation represents our findings from a survey conducted within 15 staff members who are occupying our living at the 5th floor. The survey shows that on average, a staff spends around five and a half out of eight hours working behind the computer, meaning that in around two and a half hours the computer can be sent to sleep mode in order to save energy spent. More detailed discussions are shown in [28].

d) Potential Saving from Controlling Other Appliances: Based on the measurements collected from a microwave, a coffee machine, a water boiler, and a fridge, we spot the potential saving by controlling other appliances within office environment. One can also find detail discussions on the potential saving from controlling other appliances in [25].

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

Coffee machines are common in offices and the idle consumption of such a device is high, even when it is not being used. Most measurements were 58 watt, although roughly every six hours a measurement of about 38 watt occurs when the coffee machine was idle. Thus, on average the coffee machine uses 56 watt when there is no staff member uses it. There is no need for the coffee machine to be active outside office hours which means a potential energy saving of 5900 watt (56 watt*105.5 hours) per week, which is around 50% savings of the total weekly energy consumption of the coffee machine. Potential issues with turning off the coffee machine at night and on weekends is that the machine might not be capable of recovering from long downtime. Besides the hardware limitations there might also be issues with the ‘freshness’ of the products stored inside the machine when the power is lost over longer periods of time. However, recommendations by Bush et al. [17] regarding the energy efficiency of coffee machines suggest that it should be possible to disable the coffee machine completely.

The fridge is cooled on intervals. The fridge cannot be turned off completely because the drinks and food in the fridge need to be cooled to stay fresh. Our previous research [22] shows that the fridge is capable of cooling sufficiently when only turned on for 15 minutes of every hour. During these 15 minutes the fridge is cooling at the maximum energy usage. Taking into account that the rated consumption of the fridge is 70 watt, the consumption of the fridge during those 15 minutes per hour should be around 17 watt at most. As a result, there is a difference of 0.065 kWh between a regular weekday and a day in the weekend. This would mean a saving of 0.325 kWh (5 days * 0.065 kWh) per working week and a yearly saving of 14.82 kWh (228 working days * 0.065 kWh) per fridge, which amount to around a potential energy saving of 10%.

V. RELATED WORK

Numerous researches have analyzed and shown the energy saving potential in office buildings. Lighting has been pointed out by many authors [20], [16] as an area with significant energy improvement potentials. Besides lighting, office equipment (e.g., computer and monitor) influences the energy usage to a great extend. Kawamoto et al. [26] and Webber et al. [33] show that a large percentage of computers and monitors are not turned off but in standby mode during non-office hours (40% in Japan and 75% in US). According to the authors of [33], computers and monitors in offices are found to be in standby mode for no less than 21 hours a day. HVAC systems can also contribute to the possible energy and cost savings according to several studies [14], [12]. Our solutions focus on all subsystems, i.e., lighting and office equipment for energy saving potential as well as the HVAC.

Despite the scientific interest in improving the energy consumption through BMS systems, Nguyen and Aiello [27] describe in a survey about energy intelligent systems that the three main energy consuming subsystems in buildings (i.e., HVAC, lighting and office equipment) also draw the attention of numerous studies. From the researched studies, some focus on one subsystem only, while others try to save energy for two or even three subsystems. The majority (22 out of 32) of the reviewed studies focus only on one subsystem, our solution focuses on two subsystems. Six studies focus on HVAC and lighting, three focus on HVAC, lighting and power plugs, and two others focus on lighting and power plugs only. The iSpace [7] and the Intelligent Buildings by Davidson et al. [18] are the two projects that only focus on lighting and power plugs, similar to the focus our research. The work presented in [7] differs with our research because, although it can be used for energy savings, it is focused on autonomous environments and on student bedrooms, rather than offices. In addition, the energy consumption is not monitored. Although Davidson et al. do the same conceptually [18], the system in our solution uses a different implementation. The other study, namely the GreenerBuildings project [5], considers multiple buildings, such as offices, universities and hotels, for deployment. The architectural model of the GreenerBuildings project was used as a starting point for the architectural model for our solution.
VI. CONCLUSIONS

The GreenMind system is capable of reaching the goals set out in the introduction, that is the energy saving of 7% of total building energy consumption. All subsystems, i.e., lighting system, HVAC system, workstations, and other appliances can be monitored and controlled. Experimental results confirm that significant amount of energy spent for above-mentioned subsystems could be saved by using our solutions, satisfying the saving goals that we set for our project. Specifically, 25% is the electricity saving from lighting control, the saving from HVAC control could reach at least 20%, while the same figures for workstation control and plug load control are 33% and 10%, respectively. Furthermore, the GreenMind system is a framework that allows the University of Groningen to expand its research into sustainability in new direction, such as user awareness, and provides the researchers with real and up-to-date data. The loose design of the system components means that it can be enhanced over time, exceeding the goals of this initial design, and thus provides more possibilities than the existing built-in BMS.

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