MASTER

A multi-agent system for controlling multiple comfort aspects

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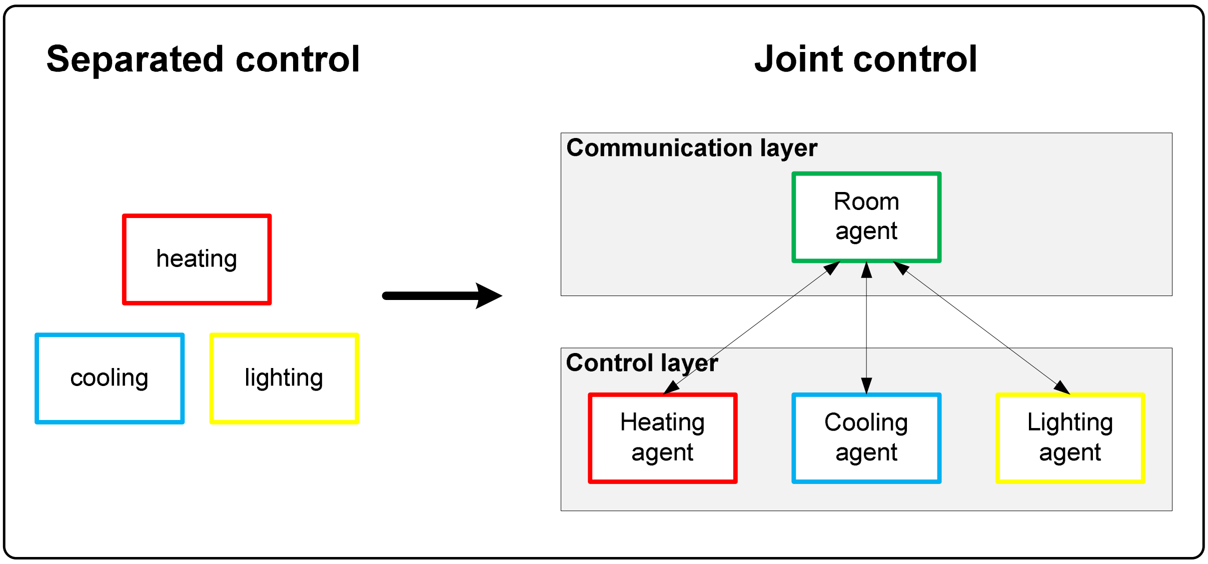

Master thesis

A Multi-Agent System for controlling multiple comfort aspects

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Eindhoven University of Technology
August 2012

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Preface

This master thesis is the conclusion of the Building Services Master program at the Eindhoven University of Technology. The subject of this research is agents which cooperate to control the temperature and lighting in a room while taking both comfort level and energy saving into account. This research is a continuation of a master project where agents were also the central part. The master project filled me with much enthusiasm to continue doing more research on agents and learn more about it.

Since the master project was mostly theoretical, this graduation project was a great opportunity to put agents into practice. The biggest challenge was the multidisciplinary approach, where three fields were combined:

1. <u>Building Services</u> (heating, ventilation and cooling)
2. <u>Building Physics</u> (natural lighting, operation of blinds)
3. <u>Computer Science</u> (programming agents, agent reasoning, agent communication)

I would like to take this opportunity to thank several people for their help and support during my graduation period. First of all, I would like to thank prof. dr. ir. Jan Hensen for his guidance and valuable advice throughout the whole project. I would also like to thank dr. ir. Rinus van Houten for his contribution to the realization of the report and for monitoring the process during my graduation. The discussions with ir. Gert Boxem helped me a lot with formulating the reasoning strategies of the multi-agent system. I am also very thankful for the help and advice dr. ir. Myriam Aries gave me in the field of lighting and also for providing me the measured data of different weather types. A special thanks goes to dr. ir. Ion Barosan of the department of mathematics and computer science who helped me with the coding of the agents and also gave me a better understanding of the procedures within Jade programming.

Furthermore, I would like to thank the staff of the Laboratory of Building Performance Simulation for their help with the experimental setup. Harrie Smulders helped me with installing all the necessary software components and realized the software connection between the agents and the sensors and actuators in the test room with Labview. Wout van Bommel has been responsible for arranging all the hardware components that were used in the test room and made the physical connections between the agents and the sensors and actuators in the test room. I would also like to thank ing. Jan Diepens for installing an alternative cooler, which fixed the problem of having insufficient cooling load for the experiments.

Chao Ming Chen
August 2012

Abstract

Studies have shown that energy savings in the field of heating and cooling as well as in the field of lighting are very possible. However, these studies usually focus on just one comfort aspect while in reality these individual comfort aspects can influence one another. The results of these studies consequently give a biased view of the true energy saving potentials.

This master thesis investigates whether higher energy savings are possible when multiple comfort aspects and their interrelationships are taken into account. For this purpose a multi-agent system (MAS) is developed. The agents in this MAS will not only have individual goals but are also able to communicate and cooperate with one another in order to achieve a common goal. The software of this MAS is written in Java and for the experiments this software program will be connected to several sensors and actuators in a test room. A test case evaluates the performance of the MAS.

The test case in this report consists of two parts. In the first part the control systems for heating, cooling and lighting work independently and are manually controlled by the occupant. In the second part the heating, cooling and lighting control become part of a MAS and are able to cooperate.

The results of this test case point out that a MAS is able to reduce the energy loads, while maintaining or even improving the comfort in the room. The agents react appropriately to changing situations and are also able to cooperate with one another.

This thesis concludes that a MAS has the ability to realize energy saving without compromising on comfort. This is mainly due to the fact that the agents within a MAS are not only able to work separately to accomplish individual goals but are also able to work as a team in order to accomplish a common goal.

Samenvatting

Studies hebben uitgewezen dat energiebesparingen op het gebied van verwarming en koeling alsook op het gebied van verlichting weldegelijk mogelijk zijn. Echter, deze studies concentreren zich normaal gesproken slechts op één comfort aspect terwijl in de werkelijkheid deze afzonderlijke comfort aspecten elkaar kunnen beïnvloeden. De resultaten van deze studies geven daarom een vertekend beeld van de werkelijke energiebesparingsmogelijkheden.

Deze master thesis onderzoekt of meer energiebesparingen mogelijk zijn wanneer meerdere comfort aspecten en de onderlinge relaties in ogenschouw worden genomen. Voor dit doel is een multi-agent system (MAS) ontwikkeld. De agents in deze MAS hebben niet alleen individuele doelen maar zijn ook in staat om te communiceren en samen te werken met elkaar om een gemeenschappelijk doel te bereiken. De software van de MAS is geschreven in Java en voor de experimenten zal dit software programma gekoppeld worden aan sensoren en actuatoren in een testkamer. Een testcase beoordeelt de prestaties van de MAS.

De testcase in dit rapport bestaat uit twee delen. In het eerste deel werken de verwarming, koeling en verlichting afzonderlijk van elkaar en worden deze handmatig bediend door de gebruiker. In het tweede deel zijn de verwarming, koeling en verlichting onderdeel van een MAS en zijn deze in staat om samen te werken.

De resultaten van deze testcase wijzen uit dat een MAS in staat is om het energieverbruik te verminderen en tegelijkertijd het comfort in de kamer te handhaven of zelfs te verbeteren. De agents reageren op de juiste manier op veranderende situaties en zijn ook in staat om met elkaar samen te werken.

Deze thesis concludeert dat een MAS in staat is om energiebesparing te realiseren zonder in te leveren op comfort. Dit is hoofdzakelijk vanwege het feit dat de agents in een MAS niet alleen in staat zijn om afzonderlijk van elkaar te werken om individuele doelen te bereiken maar ook in staat zijn om als team te werken om een gemeenschappelijk doel te bereiken.

Contents

Chapter 1 Introduction

In the last decades there is an increasing awareness of and a growing concern about energy use and its implications for the environment. The benefits of reducing energy consumption are twofold, i.e. saving money and reducing fossil fuel consumption and all the pollutants and contaminants that result from burning it.

A large part of the energy consumption can be ascribed to the building sector. Heating and cooling systems of buildings account for 30-50% of the global energy consumption [Kharseh et al., 2011]. A significant portion of the consumption is caused by the ever growing demand for better thermal comfort in terms of space heating in winter and space cooling during the hot/humid summer months [Wan et al., 2011]. Since buildings are the largest source of global energy demand, cutting emissions in this sector can be a very big step in achieving energy reduction.

Increasing use of energy in buildings

The increasing use of energy is a global problem. Figure 1 shows the electric power consumption per capita for four different continents and also the Netherlands. The graph shows a rising trend for all continents. The United States, who have the highest electric power consumption per capita, have seen this variable tripled during the last 50 years. Latin America and Asia have the lowest electricity consumption per capita, of which the latter has been witnessing a growing increase since 2000. The trend of the European Union is in between that of the US on one side and Latin America and Asia on the other. The Netherlands show a quite similar pattern compared to the EU, which means an average Dutch citizen consumes more electricity than an average Asian citizen and less electricity than an average US citizen.

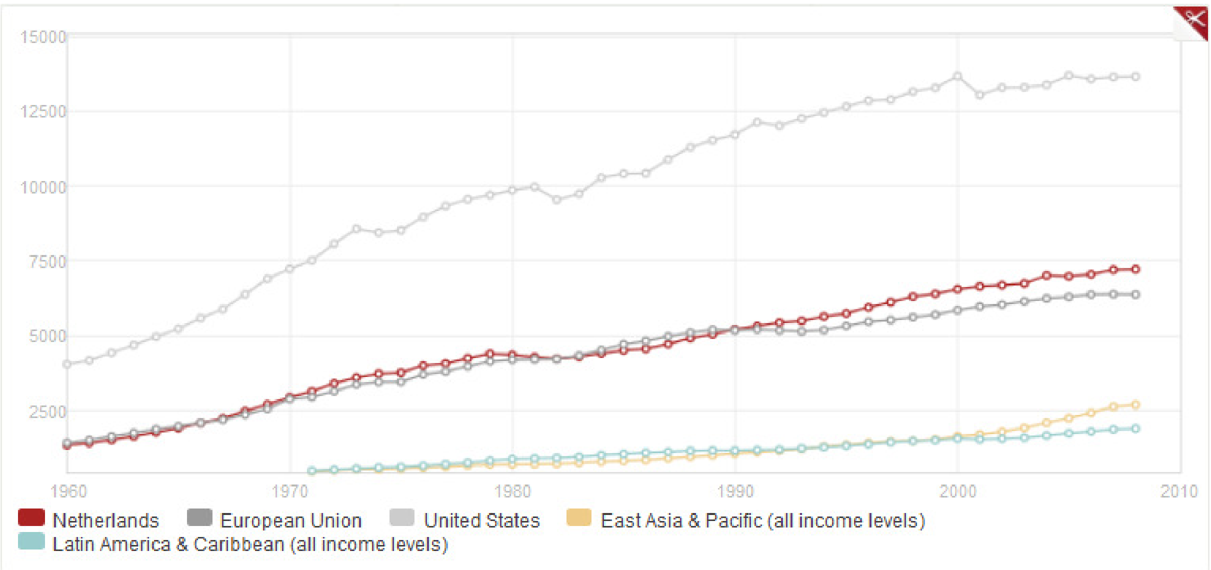


Figure 1: Electric power consumption (kWh per capita) [World Bank]

Designers and users of buildings will need to anticipate on this increase in energy consumption by taking measures to realize energy saving in buildings. This can be realized in two ways. One of the options is by reducing the energy loads, e.g., by automatically switching off the lights or lowering the room temperature in rooms. However, at the same time the users of a building like to have an increase in comfort level. This can be realized, e.g., by adapting temperature and light intensity according to each person's personal preference. This means there are conflicting goals in buildings: maximizing energy saving vs. maximizing comfort level [Davidsson and Boman, 2005]. Because when increasing the energy saving, consequently the occupants' comfort will decrease and vice versa.

Another possibility to realize energy saving is by reducing the amount of wasted energy within the built environment. An example to illustrate this problem is of finding the optimal operation temperatures in a building with a central air conditioning unit and local heating units. The main problem lies in the centralized vs. decentralized climate control. Depending on the orientation of the sun, it is very possible that one room situated at one side of the buildings needs cooling while at the same time another room situated at the other side of the same building needs heating. With conventional control methods it is difficult to find the optimal settings of a central air conditioning unit because the outside temperature and solar irradiance vary strongly from day to day [Pennings, 2009].

Studies have shown that energy savings in the area of lighting and in the area of heating and cooling are very possible. However, these studies focus on one comfort aspect only and do not consider the possibility that changing one comfort aspect may affect another comfort aspect in either a positive or negative way. The studies that investigate the energy saving potentials in the field of temperature control pay little to no attention to the lighting aspect. For example Davidsson and Boman [Davidsson, 2005] conducted simulations using a thermodynamic model of an office building whereby the radiation from the sun is neglected during the simulations. At the same time the studies that concentrate on the energy saving potentials in the field of lighting also pay little to no attention to the temperature aspect. For example Mahdavi et al. [Mahdavi, 2008] have observed users' behavior regarding the operation of lighting and shading systems in office buildings. Although heating and cooling loads were mentioned in the paper of Mahdavi, these comfort aspects were not taken into account during the observations.

The objective of this master thesis

This master thesis investigates whether higher energy savings are possible when multiple comfort aspects and their interrelationships are taken into account. The two fields of temperature and lighting are combined in order to generate a more realistic outcome of the possible energy savings in buildings when the heating and cooling aspect and also the lighting aspect are considered.

The role of the Multi-Agent System

The MAS needs to maintain a high comfort level, while at the same time reducing the energy loads. In order to accomplish this goal, the following research questions are investigated:

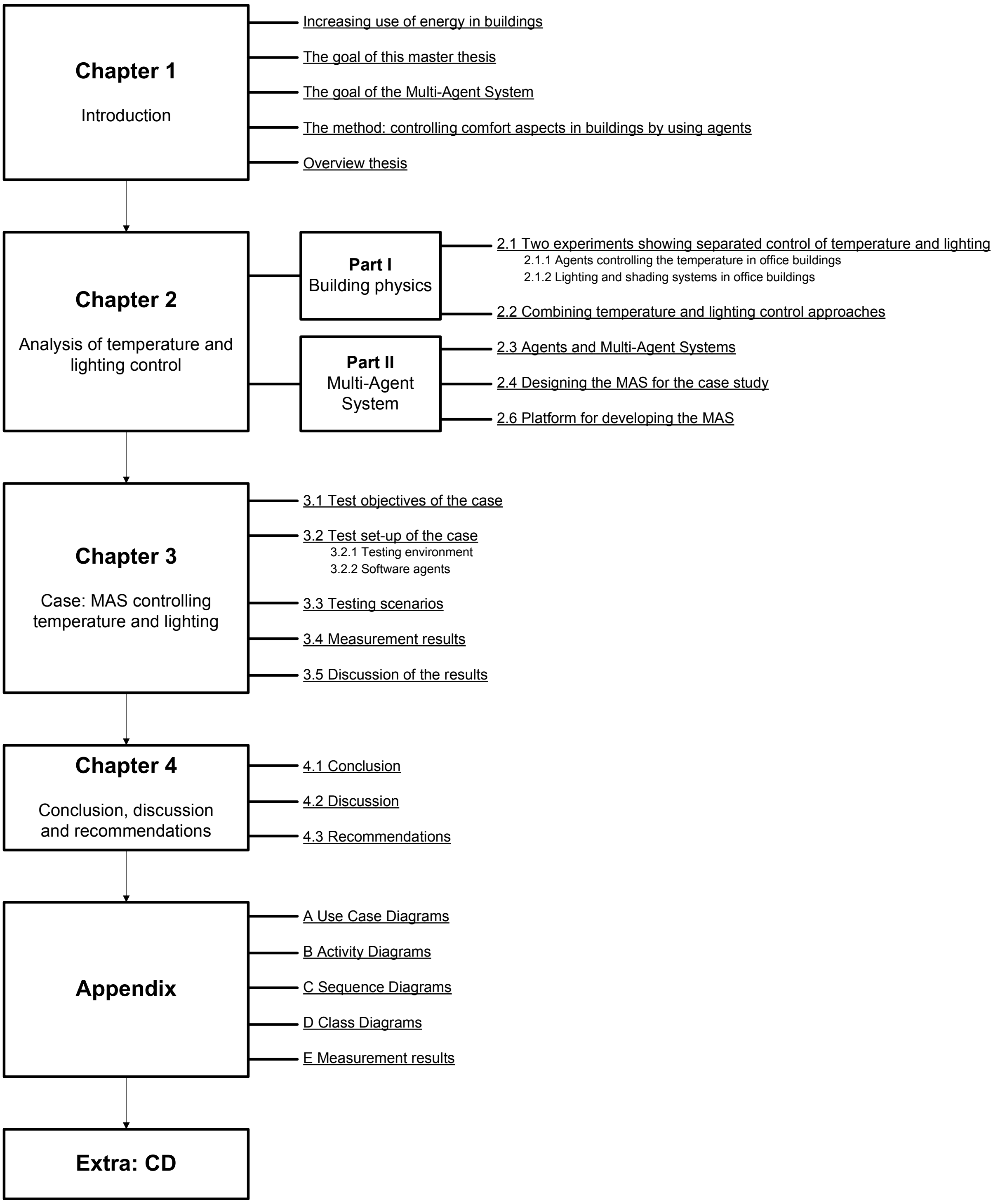
- What are the requirements for the temperature and lighting control?
- How to make sure that these separate controls are able to cooperate with one another?
- How does the decision making of this system look like?
- What are the benefits of using a Multi-Agent System

The method: controlling comfort aspects in buildings by using agents

The method that is used to improve the energy saving in buildings is to implement an intelligent system which controls and monitors different comfort parameters in the room, i.e. temperature, luminance and illuminance. Such system is designed by using agents. The main reason for choosing agents is because agents are particularly well-suited for distributed problem solving. First of all, agents are able to communicate with other agents. This communication capability makes it possible for agents to negotiate and cooperate with one another in order to achieve a common goal. Second, agents have the capability to build models of their environment, monitor the state of that environment, reason and make decisions based on that state. These skills are all very useful in the built environment. In other words, agents have all the skills that are needed to build a system which is suited for a complex environment.

Overview thesis

This master thesis "A Multi-Agent System for controlling multiple comfort aspects" is divided into five chapters. Chapter 1 presents the problem definition and the aim of this project. Chapter 2 shows the energy saving potentials in an office building and describes the development of the MAS that is used in this report. In chapter 3 the test case is explained and a case study is shown where the MAS controls both the temperature and the lighting in a test room. Chapter 4 contains the conclusion, discussion and recommendations for further research on multi-agent systems.



Chapter 2 Analysis of temperature and lighting control

This chapter is divided into two parts. The first part describes the temperature and lighting control in buildings. The second part describes how a multi-agent system can be used to control both the temperature and lighting.

Part I: Building physics

This part shows the existing temperature and lighting control in buildings and how these can be improved. In section 2.1, two experiments are shown in order to demonstrate the usefulness of implementing a MAS to control certain comfort parameters in an office room. Section 2.2 explains the reason why temperature and lighting should be considered simultaneously and not separately for control approaches.

2.1 Two experiments showing separated control of temperature and lighting

This section presents two experiments to indicate the potential energy savings in the field of two specific comfort areas: temperature and lighting. Section 2.1.1 shows the potential energy saving in buildings when applying different temperature control approaches. Section 2.1.2 shows the potential electrical energy saving for lighting in buildings when considering different energy saving scenarios.

2.1.1 Agents controlling the temperature in office buildings

A typical office building has an electrical network and a number of electrical devices connected to this network. Such office buildings can have great benefits by using a Multi-Agent System (MAS) for monitoring and controlling the temperature in the offices. This MAS can use the existing network for communication between the agents and the electrical devices of the building, i.e. the sensors and actuators. The sensor devices provide input to the MAS and the actuator devices receive instructions from the MAS. The sensor devices used by Davidsson and Boman [Davidsson, 2005] are temperature and light intensity and the actuator devices are lamps and radiators. The objectives of this MAS are both energy saving and increasing customer satisfaction through value added services.

The behavior of each agent in the MAS is determined by a number of rules that are based on the desired control policies of the building conditions. When certain events occur inside the building (like one person coming into an office room) messages are send to the corresponding agents and some appropriate rule(s) are triggered. The agents then execute the rule(s) to adjust the environmental conditions to a preferred set of values. Since a sequence of actions is needed to execute the rule(s), communication between the agents of the system and the actuator device is fundamental.

The MAS as described by Davidsson and Boman [Davidsson, 2000], consists of four main categories of agents:

- *Personal Comfort (PC) agents*, which each corresponds to a particular person. It contains personal preferences and acts on that person’s behalf trying to maximize her/his satisfaction.
- *Room agents*, which each corresponds to and controls a particular room with the goal of saving as much energy as possible. Taking into account the preferences of the persons currently in the room, it decides what values of the environmental parameters, e.g., temperature and light, are appropriate.
- *Environmental Parameter (EP) agents*, which each monitors and controls a particular environmental parameter in a particular room. They have access to sensor and actuator devices for reading and changing the parameter, and their goal is to maintain the value of the parameter decided by the Room agent.
- *A Badge System Agent (BSA)*, which keeps track of where in the building each person is situated and maintains a data base of the PC agents and their associations to persons.

The total system can be divided into three parts; the hardware (the building including sensors and actuators), the software (the MAS) and the people working in the building. Davidsson and Boman [Davidsson, 2005] have decided to simulate the hardware and the behavior of the people and let the actual MAS interact with these simulated entities instead of the actual building and people. The results of four different approaches were compared:

1) *The thermostat approach*: This is the current method of controlling the environmental parameters in most buildings. The people working in the building set the desired temperature manually. However, since most people do not lower the temperature in their offices when they go home, the temperature is assumed to be always set to 22 ^oC.
2) *The timer-based approach*: This approach is a bit more sophisticated (in fact, it may well be the smartest approach in current use). A timer starts raising the temperature at 7 a.m. to 22 ^oC in all rooms, and at 7 p.m. it starts to lower the temperature to 16 ^oC, i.e., the thermostat is set to 22 ^oC and 16 ^oC respectively.
3) *The reactive MAS approach*: When a person is in the building, the temperature of her office is set to 22 ^oC, and when she is not, the temperature is set to 16 ^oC.
4) *The pro-active MAS approach*: Makes use of the electronic diaries of the persons working in the building in order to heat up the rooms to the preferred temperature in advance.

The results described in Table 1 show that the MAS approach almost saves 40% energy compared to the thermostat approach and almost 12% compared to the timer-based approach. The pro-active approach is only slightly more energy consuming than the reactive, but will increase customer temperature satisfaction.

Table 1: The average weekly energy consumption of the four control approaches [Davidsson and Boman, 2005]

Control approach	Average weekly energy consumption
Thermostat	221.8 kWh
Timer-based	154.3 kWh
Reactive MAS	136.2 kWh
Pro-active MAS	137.0 kWh

Energy saving was only one goal of the system, increased customer satisfaction is the second goal. To calculate the degree of satisfaction, a simple linear model has been used where 16 ^oC corresponds to 0% satisfaction and 22 ^oC corresponds to 100% satisfaction. The results of the simulations are described in Table 2.

Table 2: The average degree of temperature satisfaction of the four control approaches [Davidsson and Boman, 2005]

Control approach	Average degree of temperature satisfaction
Thermostat	100.0 %
Timer-based	91.8 %
Reactive MAS	97.7 %
Pro-active MAS	100.0 %

The thermostat approach reaches the maximal degree of customer satisfaction because it keeps the desired temperature at all times. However, the price for this approach is a very high energy consumption. The current method to lower the energy consumption, i.e. using a timer-based approach, has a significantly lower degree of customer satisfaction than the MAS-based approaches. Figure 2 shows that the assumed distribution of working time is even quite favorable to the timer-based approach. For instance, if over-time work during weekends would be included, the results would be much worse while the performance of the MAS-based approaches would be still the same [Davidsson and Boman, 2005].

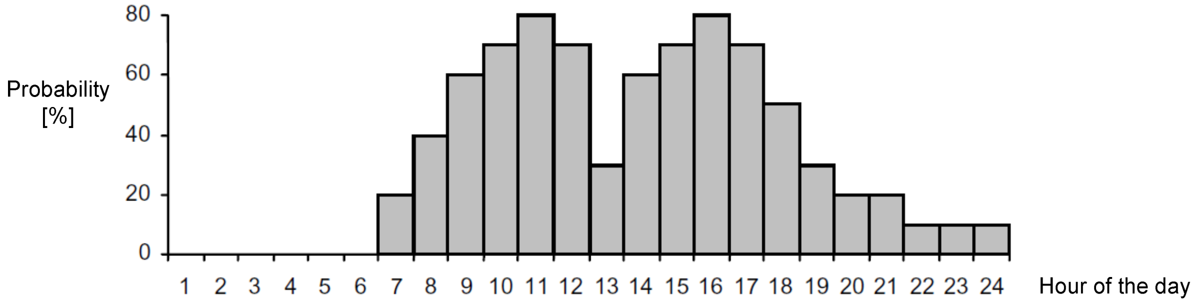


Figure 2: The distribution of working time of the persons involved (the height of a bar corresponds to the probability that the person is working in the building during that hour) [Davidsson and Boman, 2005]

2.1.2 Lighting and shading systems in office buildings

Mahdavi et al. [Mahdavi, 2008] have collected data in several offices in three office buildings to continuously monitor certain events and states (occupancy, indoor and outdoor temperature and relative humidity, internal illuminance, external air velocity and global irradiance, status of electrical light fixtures, position of shades). The results show distinct patterns in the collected data. Specifically, control lighting and shading behavior show dependencies on both the indoor and outdoor environmental parameters.

One of the three office buildings that has been used for data collection is an educational (university) building (henceforth referred to as 'FH'). The second building is a large high-rise office complex (henceforth referred to as 'VC'). An important feature of this building is that it is used as one of the major seats of international organizations, which means a very diverse occupancy profile in cultural terms. The third office building is used by a governmental organization (henceforth referred to as 'HB').

The intention of their experiment was to observe user control actions concerning the lighting and shading systems while considering the indoor and outdoor environmental conditions. The indoor parameters monitored are room air temperature (in ^{o}C), room air relative humidity (in %), ambient illuminance level at the workstation (in lx), luminaires' status (on/off), and occupancy (present/absent). The outdoor parameters monitored are air temperature, relative humidity, wind speed (in m/s), and horizontal global irradiance (in W/m^2). The vertical global irradiance incident on the façade was computationally derived based on measured horizontal global irradiance. All parameters were logged regularly every 5 minutes.

The range of data considered was limited to working days. In the case of FH and VC the data considered was between the hours 8:00 and 20:00. And in the case of HB it was between the hours 6:00 and 18:00. The collected data was mainly analyzed to develop hypothesized relationships between the nature and frequency of the control actions on one side and the magnitude and dynamism of indoor and outdoor environmental changes on the other side.

Figure 3 shows the normalized relative frequency of (intermediate) actions 'switching the lights on' (by occupants who have been in their office for about 15 min before and after the occurrence of the action) as a function of the predominant illuminance level immediately prior to the action's occurrence. Normalization in this context means that the actions are related to both occupancy and the duration of the time in which the relevant illuminance ranges apply.

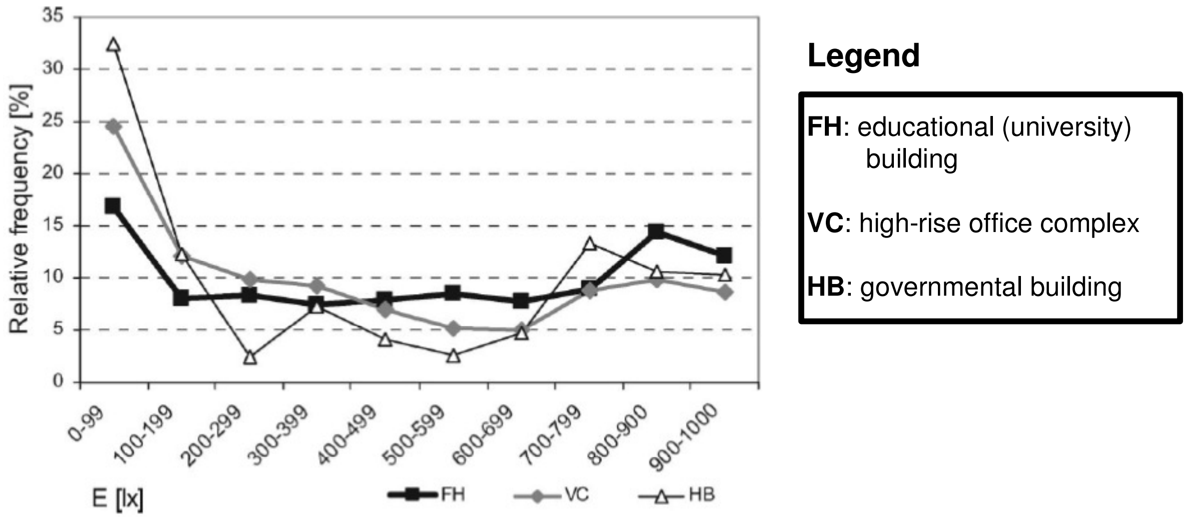


Figure 3: Normalized relative frequency of intermediate switching the lights on actions in FH, VC and HB as a function of the predominant illuminance level [Mahdavi et al., 2008]

The relationship between 'switching on the lights' actions and the predominant illuminance levels in the monitored buildings suggests that only illuminance levels well below 200 lx are likely to trigger actions at a non-random rate.

Figure 4 shows the probability that an occupant would switch off the lights when leaving his/her office as a function of the time that passes before he/she returns to the office. Occupants switch off the lights more frequently if they are going to be away from the offices for longer periods of time.

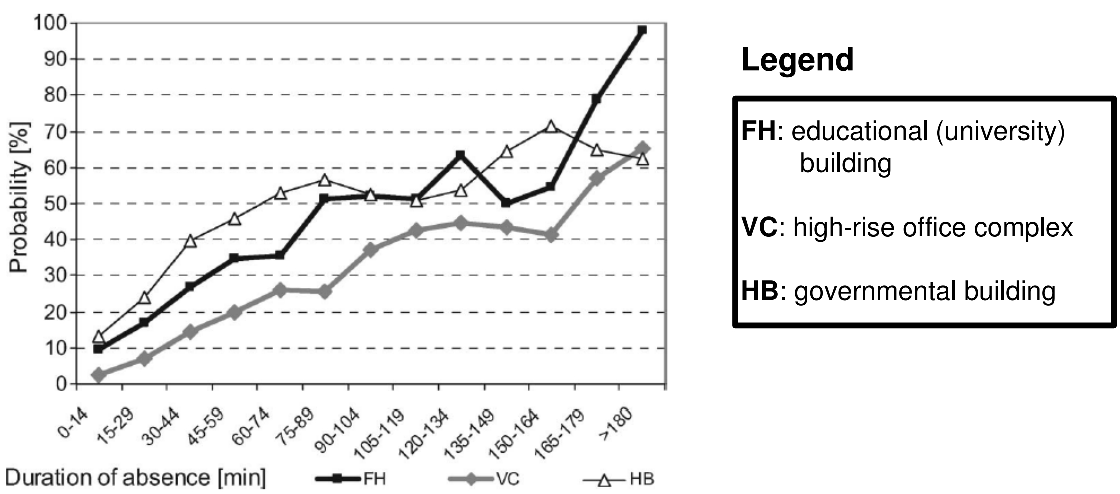


Figure 4: Probability of switching the lights off as a function of the duration of absence (in minutes) from the offices in FH, VC and HB [Mahdavi et al., 2008]

Figure 5 shows the normalized frequency of the (intermediate) 'switching the lights off' actions as a function of the predominant illuminance level immediately prior to the action's occurrence. Normalization in this case means that the actions are related to both occupancy and the duration of the time in which the relevant illuminance ranges apply. The FH and VC graphs show an increase in the rate of intermediate 'switching the lights off' actions due to higher levels of predominant illuminance levels.

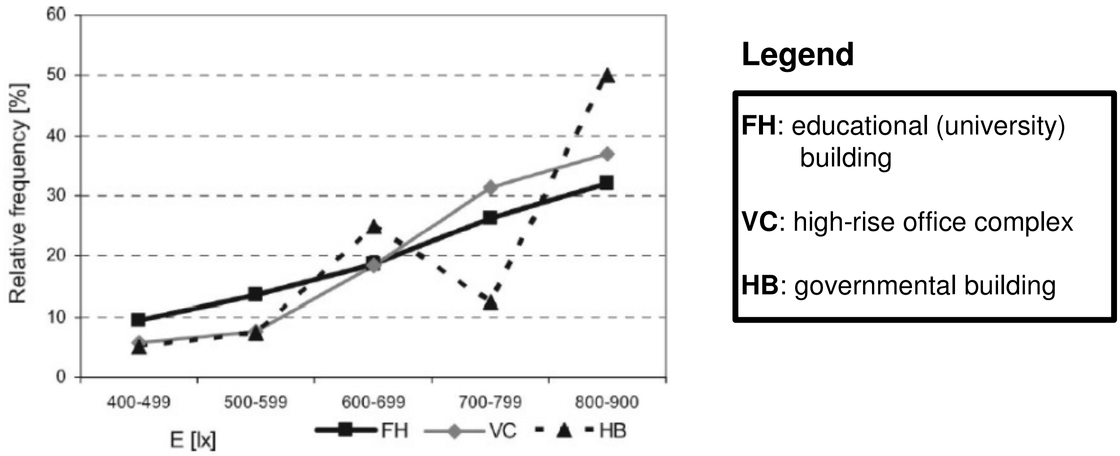


Figure 5: Normalized frequency of intermediate switching the lights off actions in FH and VC offices as a function of the predominant illuminance level [Mahdavi et al., 2008]

Figure 6 shows the normalized relative frequency of the 'closing shades' actions as a function of global vertical irradiance incident on the façade for FH and VC. Normalization in this case means that the frequency of actions (opening and closing shades) is related to both occupancy and the duration of time in which the predominant irradiance was within a certain range. In this case the definition of opening/closing actions is not only actions resulting in fully opening/closing the shades. More correctly, it means that even an incremental change (e.g. changing from 80% to 40% or changing from 20% to 40%) is considered an opening/closing action. The analysis of the 'closing shades' actions shows for FH a higher action frequency once the incident radiation rises above 200 W/m^2.

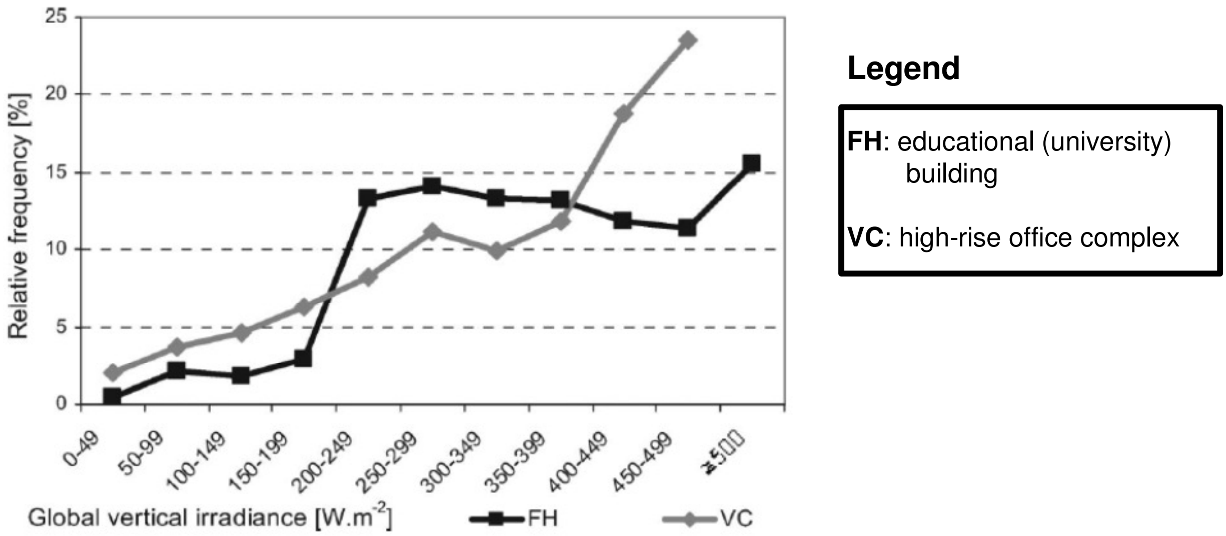


Figure 6: Normalized relative frequency of closing shades actions as a function of the global vertical irradiance in FH and VC [Mahdavi et al., 2008]

A general remark is that the environmental systems in a considerable number of office buildings may in fact be 'over-designed'. In other words, they are dimensioned for occupancy levels that seldom occur. Figure 7 and Table 3 show the saving potential of electrical energy use for lighting in the sampled offices. Thereby, two (cumulative) energy saving scenarios are considered. In the first scenario the lights are automatically switched off after 10 min if the office is not occupied. The second scenario implies an automated dimming principle, whereby luminaires are dimmed down to maintain an illuminance level of 500 lx at the workstation while minimizing electrical energy use for lighting.

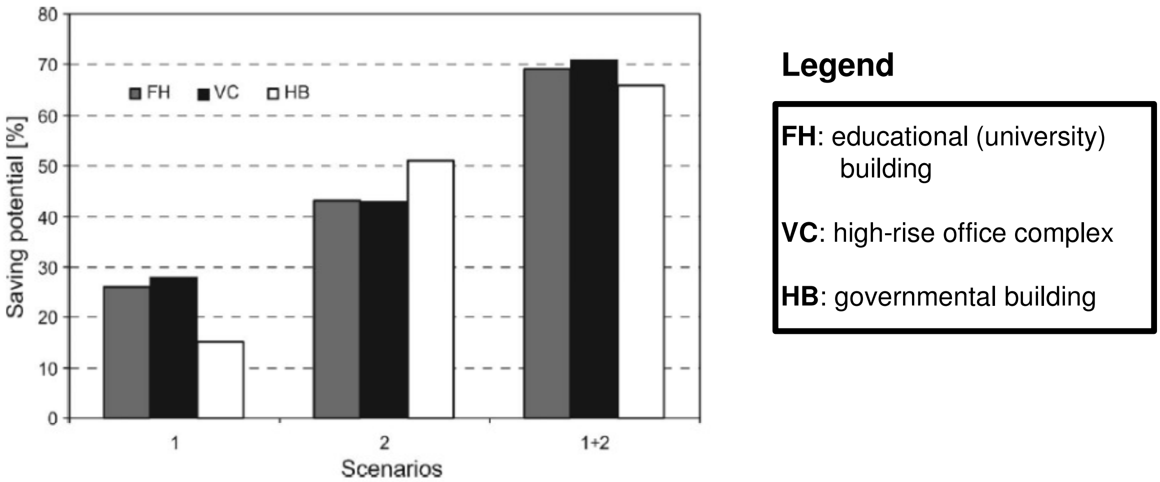


Figure 7: Saving potential for two control scenarios in view of electrical energy use for lighting in FH, VC and HB [Mahdavi et al., 2008]

The estimated saving potential in electrical energy use for lighting of the sampled offices is significant. The cumulative energy saving potential for all sampled offices is 71% for VC, 69% for FH and 66% in HB (Table 3). The cumulative annual energy saving potentials are respectively 6.8 kWh/m^2, 10.2 kWh/m^2 and 17 kWh/m^2.

Table 3: Saving potential (electrical energy for lighting) for various scenarios and buildings [Mahdavi et al., 2008]

Building	Saving potential in	Energy saving scenarios		
		1	2	1 + 2
HB	%	15	51	66
FH	%	26	43	69
VC	%	28	43	71
	$kWh\ m^{-2}\ a^{-1}$	6.8	10.2	17.0

2.2 Combining temperature and lighting control approaches

When considering the two comfort aspects separately, i.e. heating and cooling on one hand and lighting on the other hand, energy saving is definitely possible when making use of a multi-agent system. The energy saving for heating and cooling can go up to almost 40%, while the energy saving potential for lighting is even higher and can possibly reach up to 70%. These percentages show the great theoretical potential of energy saving in buildings. But, in practice, these percentages may be different, because other aspects that can influence the comfort in the room are not taken into account.

Since these high percentages for possible energy savings are possibly not entirely realistic, the aim of this report is to show the possible energy savings of a room when taking both comfort aspects into account. For this purpose a MAS is created (see section 2.4) which controls both the temperature and the lighting in a room. The temperature control is divided into a heating agent which takes control of the heating and a cooling agent which takes control of the cooling in the room. The lighting control is taken care of by a lighting agent. These agents each have their own reasoning methods to achieve individual goals, but since these individual goals can conflict with one another, e.g. the lighting agent deciding to raise the blinds to save energy on lighting can have a negative influence on the cooling load, communication between the agents is very important. In all cases every single agent should be prepared to sacrifice their own individual goal in order to achieve a more important common goal. This willingness to cooperate between the agents shows the strength of a MAS.

Part II: Multi-Agent System

This part shows the features and possibilities of a multi-agent system (MAS) and explains the design steps of the MAS that is used in this report. Section 2.3 describes what agents are and how they work. Section 2.4 shows step-by-step how the MAS for the test case is build. In section 2.5 a platform is chosen for the development of the MAS.

2.3 Multi-Agent Systems and agents

A multi-agent system, or in short a MAS, consists of two or more agents that are able to cooperate in order to achieve a common goal. But what are agents exactly? Unfortunately, there is no universally accepted definition of this term. This can be partially explained by the fact that various attributes associated with agency are of differing importance for different domains. For example, for some applications agents must be able to learn from their experience, while for other applications learning is undesirable. Nevertheless, some sort of definition is needed. In this report the following definition will be used: “An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives.” [Wooldridge, 1999].

Agents are simply computer systems that are capable of autonomous action in some environment in order to meet their design objectives. But now the question remains: what makes an agent intelligent? One of the things an intelligent agent must be is flexible. Wooldridge describes flexibility with the following three aspects:

1. pro-activeness: intelligent agents are able to exhibit goal-directed behaviours by taking the initiative in order to satisfy their design objectives;
2. reactivity: intelligent agents are able to perceive their environment, and respond in time to changes that occur in it in order to satisfy their design objective;
3. social ability: intelligent agents are capable of interacting with other agents (and possibly humans) in order to satisfy their design objectives.

Pro-activeness basically comes down to goal directed behaviour: the procedure is simply a plan or recipe for achieving the goal. This programming model works especially well for functional systems. These systems take an input x and produce an output y using some function f(x). But for non-functional systems, this simple model of goal directed programming is not acceptable. In particular, it assumes that the environment does not change while the procedure is being executed. If the environment does change, then the chosen function f(x) can produce the wrong output. Another assumption this simple model makes is that the goal, the reason for executing the procedure, remains valid until the procedure terminates. But if the goal does not remain valid then there is no reason to continue executing the procedure.

In dynamic environments[1], blindly executing a procedure without regard to whether the assumptions are valid is a poor strategy. In such environments, an agent must be reactive instead of goal directed. It must react to events that occur in its environment, where these events affect either the agent's goals or assumptions.

So, agents must attempt to achieve their goals systematically, but they should not blindly execute the procedures to achieve those goals. And also, agents must be able to react to new situations, but they should not continually react to new situations. It is not a surprise that achieving a good balance between goal directed and reactive behaviour is hard. This is not only true for agents, but also for humans. There are enough examples of managers who continue working on a project that is doomed to failure, or managers who jump from one project to another without ever pursuing a goal long enough to achieve anything. This problem of finding a good balance is still one of the key problems for an agent designer.

An agent designer also has to be aware of social ability. Social ability is not just exchanging bits of information from one source to another. It is an agent's ability to negotiate and cooperate with other agents in order to achieve a goal. In a multi-agent environment, social ability plays a crucial role.

An agent is not the same as an object, there are definitely differences between the two. The three most important differences are the following [Wooldridge, 1999]:

1. agents embody stronger notion of autonomy than objects, and in particular, they decide for themselves whether or not to perform an action on request from another agent (a very nice slogan: "Objects do it for free, agents do it for money");
2. agents are capable of flexible (reactive, pro-active, social) behaviour, and the standard object model has nothing to say about such types of behaviour;
3. a multi-agent system is inherently multi-threaded, in that each agent is assumed to have at least one thread of control.

There are numerous of fields where a multi-agent system can be employed in order to improve the efficiency of certain applications. Wang et al. [Wang, 2008] investigated a Cybernetic Transportation System, which is composed of a fleet of driverless vehicles. This system is expected to provide public transport services with on-demand and door-to-door capabilities. For this study, a distributed fleet planning algorithm based on MAS was used, where each driverless vehicle was represented by an agent. The outcome was that the cooperation and competition between the agents lead to the transport tasks being completed more efficiently.

Chen et al. [Chen, 2010] used multi-agent technology to construct a multi-section flexible manufacturing system model. Several dispatching rules were tested, such as shortest processing time, first come first serve and earliest due date. The result was that using multi-agent technique can enhance the production efficiency of the manufacturing system.

This report, however, will focus on implementing a MAS in the built environment. But what can be learned from aforementioned examples is that agents are able to process actions in parallel, which is a crucial ability in complex environments. Sequential processing is not suited for running multiple control mechanisms at the same time.

[1] A dynamic environment is one that changes in ways beyond an agent's control. The physical world is a highly dynamic environment [Wooldridge, 1999]

2.4 Designing the MAS for the case study

The MAS in this report needs to be able to monitor and control both the temperature and the lighting in an office room. Its objectives are twofold: (i) maintaining a high comfort level and (ii) reducing the energy loads. Since these two goals are equally important the MAS is separated into two layers, i.e. a comfort layer and an energy saving layer (Figure 8). Each individual layer is responsible for only one of the two goals.

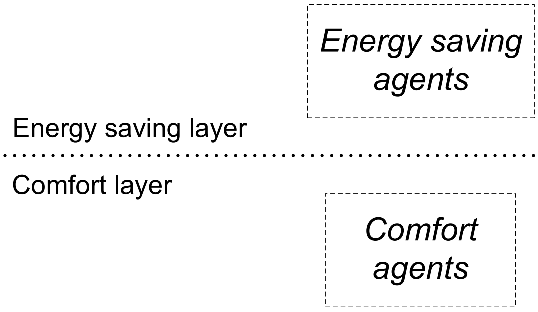


Figure 8: The MAS is divided into two layers. The boxes with dashed lines indicate 'default' systems and these need to be filled in with one or more agents

Comfort layer

The comfort layer is responsible for providing a good comfort for the occupant inside the room. In this report only two comfort aspects are considered: temperature and lighting. The temperature aspect consists of two components, i.e. heating and cooling (Figure 9).

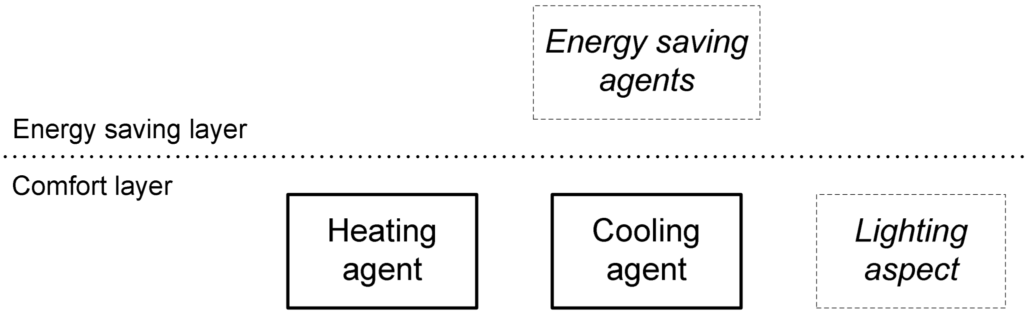


Figure 9: The temperature aspect of the comfort layer is divided into two agents, i.e. Heating agent and Cooling agent. These two agents are final, the boxes with dashed lines are still in its default form.

Temperature aspect

The only difference between the heating and cooling component is that one of these controls the heating and keeps the temperature above a certain threshold while the other controls the cooling and keeps the temperature below a certain point. Although the reasoning and coding of these two components are very similar, the heating and cooling components are still placed in two different agents instead of put together into one Temperature agent. This is done for two reasons: clarity and convenience in terms of coding.

Clarity because it is clear right away what aspect the agent controls. For instance when using a Temperature agent in an existing office room, it is not directly clear whether the agent controls the heating or the cooling or both. But when this Temperature agent is separated into a Heating agent and a Cooling agent it is immediately clear what aspect the agents control and also if one of them is missing, e.g. a room without cooling would only have a Heating agent and no Cooling agent.

The second reason for splitting the temperature control into a heating and a cooling part is for coding convenience. When changes need to be made in the software code of either the heating or the cooling, it is much more convenient when having to edit the file of just one of the agents while leaving the file of the other agent unchanged, instead of having to edit a file which contains the coding of both components and potentially mess up the code of the component which should not be changed at all. An example of this problem is when the radiator is not the only option for heating, but also the ventilation air can be used for heating. In this case the software code of the heating needs to be changed while the software code for cooling stays the same.

Lighting aspect

Now that the temperature aspect has been described, the lighting aspect will be evaluated. Just like the temperature also the lighting consists of two parts, i.e. natural lighting and artificial lighting. Natural lighting is controlled by raising or lowering the blinds and artificial lighting is controlled by a light switch. However, in contrast to the temperature aspect, the lighting will not be divided into two parts (Figure 10). The main reason for this is that it is unnecessary to do so. First of all, the natural lighting as well as the artificial lighting need the same sensor inputs, i.e. luminance and illuminance. So it is more convenient when the sensors would only have to send the values to just one agent. Second, the operation of the blinds and the artificial lighting are interrelated to each other, which means that cooperation between these two systems is important for energy savings. So when the blinds and the artificial lighting would be separated into two agents, a lot of extra communication is needed between these two agents in order to cooperate, while when having the blinds and the artificial lighting united in one agent all this extra inter-agent communication is not needed.

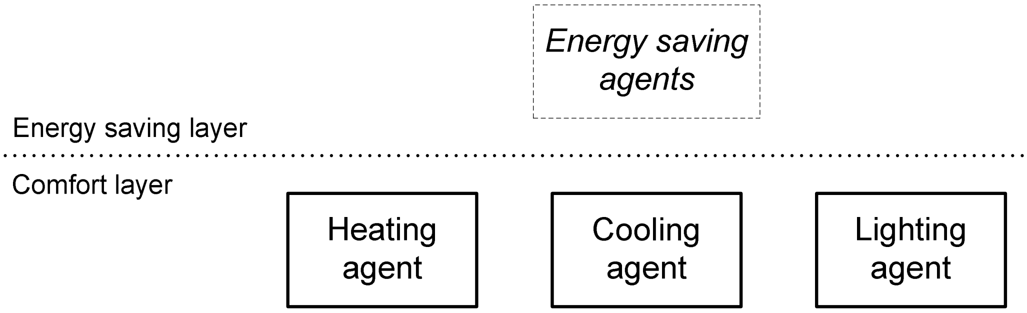


Figure 10: The comfort layer consists of three agents. The agents in the comfort layer are final, the energy saving layer still needs to be filled in

One might argue that it is not directly clear whether this Lighting agent only controls the light switch or that it also controls the blinds, which is basically the same argument that was used to decide for splitting the Temperature agent into two separate agents. This argument is countered by the argument that has been stated before, namely the fact that extra communication is needed which unnecessarily makes the agents more complex. Also the argument of coding convenience is not relevant because the lighting control and the blinds control are complementary methods that both produce the same effect, which is increasing the light intensity in the room, while the heating and cooling control produce different effects, increasing the temperature and lowering the temperature respectively.

Energy saving layer
Now that the agents for the comfort layer have been decided, the energy saving layer will be evaluated. The energy saving layer is responsible for controlling the energy loads. Providing a good comfort in a room is very important, but it is also important to keep track of the energy loads and the costs that come with it. For instance, when the price of energy is high it may be wise to (temporarily) reduce the energy consumption to prevent high energy costs. Obviously there needs to be some kind of balance between energy saving and creating a high comfort level. In contrast to the comfort layer, the energy saving layer only consists of one agent, specifically the Room agent (Figure 11).

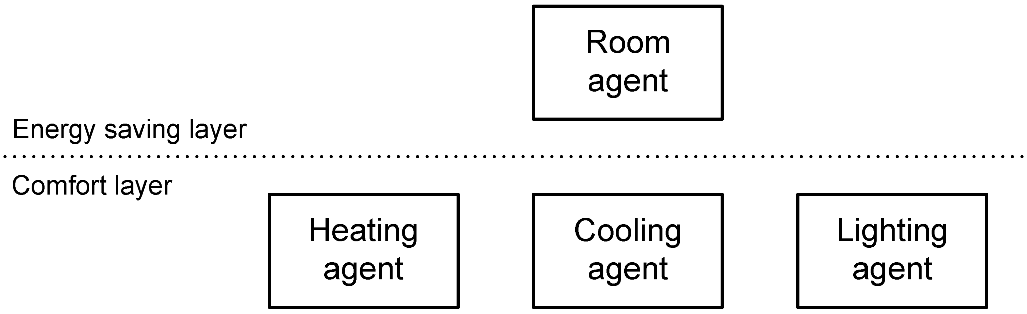


Figure 11: The comfort layer consists of three agents and the energy saving layer consists of only one agent

Depending on the energy price the Room agent determines whether energy should be saved and by how much. The agent uses a utility function (see intermezzo section 3.2.2) to calculate the degree of energy saving. The higher the energy price, the higher the energy saving recommendation. When the price changes, the Room agent gives instructions to the agents in the comfort layer, if necessary. This means that the Room agent must be able to communicate with the other agents.

Inter-agent communication
Figure 12 shows the communication lines between the agents (see also appendix A for a graphical representation of the interactions between agents). This communication between the agents is essential because without communication the agents would all act separately and are not able to cooperate. The Room agent is able to communicate with all three agents in the comfort layer. However, there are no communication lines between the agents in the comfort layer mutually. This means that the comfort layer agents are not able to directly communicate with one another, though these agents certainly are able to indirectly communicate with one another via the Room agent. The reason for this is simple, these three agents do not need to communicate with one another because these agents only care about completing their own individual goals and are neither interested in the goals of the other agents nor interested in energy saving issues. The Room agent, however, does look at the overall performance of the system and hence needs to be able to correct other agents if one does not operate to the benefit of the common goal.

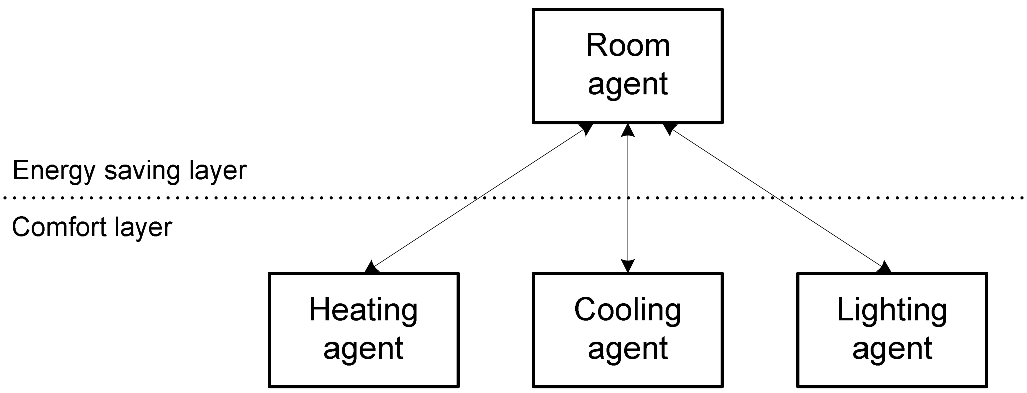


Figure 12: The MAS agents including communication lines

The communication lines between the Room agent and the three other agents operates in both directions. This means that the Room agent is able to send messages to the Heating, Cooling and Lighting agent, but these three agents are also able to send messages to the Room agent. Messages send by the Room agent are generally instructions for saving energy and messages send by the three comfort layer agents are requests to perform an action, e.g. turn on the heating or cooling, raising or lowering the blinds, etc (see appendix C for illustrations of these interactions). However, the three comfort layer agents do not need to send a request every single time before performing an action. Since the agents are autonomous, they are also able to make decisions on their own.

2.5 Platform for developing the MAS

A lot of different agent platforms exist that help the software engineer in developing multi-agent systems. However, since agent orientation is a very broad field which covers topics such as agent organization, agent behavior and messaging, most of these platforms focus on specific objectives and therefore cannot address all important aspects of agent technology equally well [Braubach et al., 2005]. In this field a distinction can be made between two important categories of platforms, i.e. middleware- and reasoning-oriented systems. The first category deals with FIPA-related issues such as interoperability and various infrastructure topics like white and yellow page services. This makes agent middleware an important building block from which agent technology can be developed. The second category focuses on the behavior model of an agent where rationality and goal-directedness are important aspects.

Since the categories mentioned above are both important for the development of the MAS in this thesis, an agent platform needs to be found which supports both middleware and reasoning. An existing mature middleware platform which is widely in use is the JADE platform. JADE (Java Agent Development Framework) is a software development framework for multi-agent systems and applications matching the FIPA standards. This platform possesses all the necessary components, e.g. agent development, agent management, debugging tools, efficient messaging, and is also FIPA-compliant [Bellifemine et al., 2010]. Another advantage is that the internal agent concepts are not restricted by this platform, which gives developers the possibility to realize any kind of agent behavior.

For the development of agents ordinary Java IDEs (Integrated Development Environments) such as Eclipse can be used. Eclipse is a programming environment which includes numerous functions that developers otherwise would have to hand code. This platform is managed by the nonprofit Eclipse Foundation, which means the entire development platform is free to use. Also, since Eclipse is built with Java, it runs on multiple platforms. However, it can also help build applications in other languages such as C, C++, Cobol and HTML [Geer, 2005]. The power of Eclipse is that different plug-in tools can be integrated into the platform so that it can work with numerous programming languages and applications (Figure 13). Plug-ins written for Eclipse can work directly with any other plug-in for the platform.

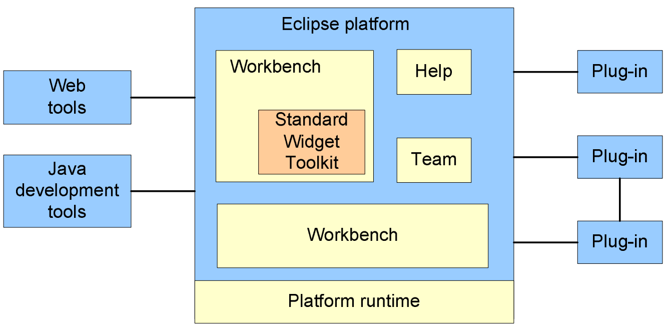


Figure 13: Eclipse platform after the example of David Geer [Geer, 2005]

Chapter 3 Case: MAS controlling temperature and lighting

This chapter describes the development of the test case and the testing environment for the multi-agent system. In section 3.1 the objectives are described. Section 3.2 explains the test set-up which consists of a software model and a test chamber. Section 3.3 describes the scenarios that are used for the experiments. In section 3.4 the results of the experiments are shown. In section 3.5 a discussion follows on the results.

3.1 Objectives of the test case

To put the MAS into practice a test case is used. This test case consists of several scenarios that illustrate the differences between a room controlled manually and the same room with MAS control. The objectives of this test case are the following:

- Comparing the comfort levels of the two approaches
- Comparing the energy loads of the two approaches

3.2 Setup of the test case

In section 3.2.1 the controlled test room is described in which the MAS will be tested. Section 3.2.2 explains the operation and reasoning of the MAS.

3.2.1 Testing environment

The experiments are conducted in a test room (ID 1785) in the BPS Laboratory in the Vertigo building on the TU/e campus. This room is equipped with the following control systems:

- An air inlet which provides both ventilation and cooling. This air inlet is positioned in the center of the room. The power of the chiller which provides the cooling is 5,1 kW.
- Luminaires on the ceiling that provide (artificial) lighting. Although this light is steplessly variable, it is only used as an on/off switch in the experiments. The power of the lights is 230W.
- One vertically placed panel consisting of many fluorescent tubes. This light panel represents an exterior window and imitates the effect of sunlight falling into the room. Since this light is steplessly variable it's also suitable to mimic blinds.
- An electric radiator which provides heat to the room. This radiator is placed directly below the vertical light panel. The power of the radiator is 1250W.
- A door which can be opened and closed mechanically.

For the experiments the MAS needs to receive information about the environmental parameters in the test room in order to function properly. This information enables the MAS to create a perception of the room and leads to actions of the agents if the conditions in the room do not match the occupant's preferences. The input for the agents are provided by the following sensors:

- Temperature sensors (internal room temperature, external temperature and air inlet temperature).
- Photometer (aimed at the light panel).
- Lux meter (placed on a table in the room).

The MAS also needs actuators in order to be able to actually change the environmental conditions of the room. When the input from the sensors do not match the desired conditions of the room, the MAS runs a sequence of actions to condition the room to the right values. The agents give instructions to the following actuators:

- The heating agent, which turns the radiator on or off.
- The cooling agent, which turns the cooling in the air inlet on or off.
- The lighting agent, which turns the luminaires on or off and also modifies the light intensity of the light panel.

For the experiments in the test room, three additional agents are needed on top of the MAS agents. These three agents are (see also appendix D for the class diagrams of these agents):

1. Sensors agent.
2. DailyProfile agent.
3. Person agent.

The sensors agent

The sensors agent consists of five sensors, i.e. three temperature sensors, one lux meter and one photometer, and measures real-time values both inside and outside the test room. The three temperature sensors measure the temperature inside the test room, the temperature of the inlet air and the temperature outside the test room. The lux meter measures the illuminance on the table in the room. The photometer measures the luminance coming from the light panel which mimics the sunlight.

The sensors agent receives the measured values from its sensors on regular intervals and passes these values on to the relevant agent. The temperature values are passed to the heating and cooling agent and the luminance and illuminance values are passed to the lighting agent.

The DailyProfile agent

Since the test room has no windows, a vertically placed luminaire is used to represent an exterior window. The lights in this luminaire can be dimmed or brightened in order to mimic sunlight. The DailyProfile agent is used to define the outside lighting levels. Hereby two profiles are considered: a clear sky and a clouded day. The variables that are used in this thesis to describe the outside lighting are the luminance and the illuminance. For both profiles real measurement values[2] are used. The DailyProfile agent passes the luminance and illuminance values to the lighting agent.

The person agent

Since there are no real persons involved during the experiments, a person agent is used to simulate a real person. The benefit of using simulated persons instead of using real persons is that user actions, e.g. entering the room, opening a door, turning the lights on, etc., always occur at scheduled times. This makes the results of the various experiments better comparable. Two different person profiles are considered: energy waster and energy saver. The energy waster does not care about energy savings at all, e.g. he leaves the door open when he turns the radiator on, he never turns the lights off when he leaves the room. The energy saver is very aware of energy consumption, e.g. he sets the thermostat one degree lower than the energy waster during winter, he always turns the lights off when he leaves the room.

3.2.2 Software agents

The MAS that is used in the tests consists of four different agents (see also appendix D for class diagrams of these agents): the heating agent, the cooling agent, the lighting agent and the room agent. Three of these agents, i.e. the Heating agent, Cooling agent and Lighting agent, are responsible for providing a good comfort level for the occupant in the room. These agents are therefore directly connected to the sensors and actuators in the room and are able to give instructions to certain electrical devices in order to change the room conditions. The fourth agent, i.e. the Room agent, has no direct connections with the room at all. Instead this agent is linked to the three other agents and thus has an indirect influence on the climatic conditions in the room. The objective of this agent is to save energy. Since the objective of this agent can sometimes conflict with

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[2] These measurement values are provided by dr. ir. Myriam Aries. The values are from measurements conducted on May 25th of 2012 on the Vertigo building.

the objectives of the three other agents, the Room agent is provided with a reasoning function which helps the agent to decide when and how to save energy.

Some general rules (or constraints) of the MAS:

- When a person is in the room, the temperature, luminance and illuminance are adapted to his/her personal preferences, unless the Room agent opts for energy saving measurements.
- When the room is empty the heating, cooling and lighting are automatically turned off.
- The door is always closed first before the heating or cooling is turned on.
- Decisions of the Room agent always overrule decisions made by the other agents.
- The temperature outside the room is the temperature of the laboratory and this temperature cannot be controlled by the MAS.

The heating agent
The job of the heating agent is to check whether the heating should be turned on or off. For this task the agent has the following sensors at its disposal: a temperature sensor and a presence sensor. The temperature sensor measures the temperature inside the room. Whilst the temperature is above a certain threshold the heating stays off, but when this temperature drops below this point the heating is turned on. The presence sensor indicates whether there is someone present in the room or not. When there is someone present, the heating heats up the room to the desired temperature, which is based on the preferences of the person present and on energy saving considerations. Whilst there is no one in the room, the heating is turned off in order to save energy. However, since there are no real test persons used for the experiments in the testing room, no actual presence sensor is used. Instead this presence status, which can be either true or false, is given by the person agent.

Furthermore, the heating agent also has two other indicators: the preferred temperature of the user inside the room and the status of the heating. The preferred temperature is user dependent and is given in by the person agent. The status of the heating can either be true or false and indicates whether the heating in the room is on or off. Only the heating agent keeps track of this variable. The reasoning of the heating agent is shown in appendix B.

The cooling agent
The job of the cooling agent is to check whether the cooling should be turned on or off. This agent is very similar to the heating agent, except for the fact that this agent deals with cooling instead of heating. This means that the cooling agent makes use of the same sensors as the heating agent, i.e. temperature sensor and presence sensor, and also shows a lot of resemblance in the reasoning method. But the difference however is that the heating status indicator is replaced with the cooling status indicator. The reasoning of the cooling agent is shown in appendix B.

The lighting agent
The job of the lighting agent is to guarantee the visual comfort in the room. For this task the agent has the following sensors at its disposal: a photometer, a lux meter and a presence sensor. The photometer measures the luminance inside the room. Luminance is a measure of the luminous intensity per unit of area of light travelling in a given direction and describes the amount of light that passes through a particular area. Whilst the luminance is below 4000 cd/m^2, glare is not an issue and the blinds have no restrictions. But when the luminance exceeds this level the blinds must be lowered to prevent glare. The lux meter measures the illuminance inside the room. Illuminance is the total luminous flux on a surface and measures how much the light illuminates the surface. While the illuminance is at least 500 lux on the user’s desk no extra lighting is needed, but when the illuminance drops below this point extra lighting needs to be provided by either turning on the artificial lighting in the room or by raising the blinds in order to create extra natural lighting. Obviously natural lighting is preferred because this method does not cost energy, aside from the

energy required for raising the blinds, but the drawback of using sunlight is the heat load that comes with it. When choosing for natural lighting at the wrong time the solar heat load puts a great burden on the cooling systems. The presence sensor is, for the same reasons as explained for the heating and cooling agent, not a hardware device but instead a presence status which indicates whether someone is present in the room or not.

Furthermore, the lighting agent also has two other indicators: the status of the lighting and the status of the blinds. The status of the lighting can either true on or false and indicates whether the artificial lighting in the room is on or off. The status of the blinds is a number between 0 and 5 and indicates the brightness of the light coming from the vertical light panel in the test room. Only the lighting agent keeps track of both these variables. The reasoning of the lighting agent is shown in appendix B.

The room agent

The job of the room agent is to check for messages from the heating agent, cooling agent and lighting agent and to reply on these messages (see appendix B). These messages are in the form of requests that vary from agent to agent. The heating agent can send a request to turn the heating on if the temperature in the room is too low, while the cooling agent can send a request to turn the cooling on if the temperature in the room is too high. The lighting agent however can send two different types of requests, i.e. (i) a request to raise or lower the blinds or (ii) a request to turn the lights on, depending on the circumstances both inside and outside the room.

After receiving a message, the room agent decides to approve the request, to decline it or to approve under a certain condition. After approving a request the corresponding action is executed. But when a request is declined the corresponding action is not executed. And in order to prevent this same request being send repeatedly until it is approved, a timer is set so that this same request cannot be send before this timer expires. The third option a room agent has is to approve the request but only under a certain condition. This occurs in the event that a heating agent sends a request for turning the heating on or when the cooling agent sends a request to turn the cooling on. When the room agent receives such a request it determines whether it is sensible to turn the heating or cooling on when taking the price of energy into account. When the price is low the heating or cooling can be turned on without any restrictions. But when the price is high the room agent sends a counterproposal with restrictions on heating or cooling, e.g. the heating can be turned on only if the room temperature drops more than 2 ^{o}C below the preferred temperature of the occupant in the room or the cooling can only be turned on if the room temperature rises more than 2 ^{o}C above the occupant's preferred temperature.

However, since cost is expressed in monetary values and comfort is not, instead it can for instance be quantified by using PMV values, these variables are not easily intercomparable. In order to make it possible for the room agent to make a well considered decision in every situation when having to choose between extra comfort or saving energy, a utility function is needed.

Intermezzo: What is a utility function?

"A utility function is a mathematical function that gives a numerical value that corresponds to the level of utility a consumer attains" [Ahlersten, 2008]. For instance, a room temperature of 22 ^{o}C would lead to a higher level of utility than a room temperature of 5 ^{o}C.

The utility function described below is not per definition the most optimal utility function for every possible office room, but is only intended for testing purposes. It is only used to demonstrate how a change in energy price affects the reasoning of the MAS.

The utility function in the MAS is a function of the room agent to determine whether the heating or cooling can be turned on depending on the actual price of energy. Without this utility function there would be no restrictions for heating and cooling, which would mean that from a certain price level onwards the costs for keeping an optimal temperature in the room would become too high. The utility function provides a balance between comfort and energy costs.

The utility function consists of two variables, i.e. profit and cost, where profit is an indication of the comfort in the room and cost represents the cost of energy. The aim of this function is to keep the profit variable as high as possible and keeping the cost variable as low as possible. In this respect the profit is regarded as a positive variable, the higher the better, and the cost is regarded as a negative variable, the lower the better. This leads to the following utility function:

$$Utility = profit - cost \tag{3.1}$$

The profit variable is a function in itself which depends on the difference between the occupant's preferred temperature (T_{user}) and the agent's advised temperature (T_{agent}), see equation 3.2. This difference will henceforth be referred to as ΔT, see equation 3.3.When this ΔT equals zero the comfort variable is at its maximum value, in other words the comfort in the room is optimal. The more the thermostat setpoint deviates from the occupant's preferred temperature, the lower the profit value.

The precondition of this formula is that the absolute difference between T_{user} and T_{agent} cannot be higher than 3. This means that the agent's advised temperature can never be more than 3 ^{o}C above or below the occupant's preferred temperature. The reason for this is to ensure a minimum and maximum temperature boundary. This precondition also explains the constants in the formula. When there is no difference between the agent's advised temperature and the occupant's preferred temperature, the profit value is at its maximum, which is 1 in this case. But when ΔT is maximal, the profit is at its minimum, which is -1 in this case.

$$Profit = -\frac{2}{9}(T_{user} - T_{agent})^2 + 1 \tag{3.2}$$

$$\text{or: } Profit = -\frac{2}{9}(\Delta T)^2 + 1 \tag{3.3}$$

The cost variable is also a function in itself which depends on (i) ΔT and (ii) the price of energy. The ΔT and price are interrelated in this formula. When ΔT equals zero it means indeed that the comfort in the room is optimal, but at the same time this also means that the energy load is at its highest. When making concessions to comfort, the energy load will also go down. The price of energy corresponds to the actual price on the energy market. However, for flexibility purposes in the experiments the price variable in the formula is made up for the different experiments and thus in this master thesis not coupled to the real price of energy.

Another aspect of the cost function is that it has two variants, one for heating (equation 3.4) and one for cooling (equation 3.5). The reason there are two variants is because the ΔT for heating on the one hand and cooling on the other hand work opposite to each other. A lower ΔT means there is less heating required and thus there will be a lower energy load, while for cooling a higher ΔT means a lower energy load. The constants in both these formulas are chosen in such a way that gradual price changes affect the reasoning of the MAS.

After calculating both the profit variable and the cost variable, the outcome of the different ΔT's are compared and the ΔT that leads to the highest utility value is the ΔT that the room agent will keep as guideline for heating or cooling.

$$Cost = \frac{100*\Delta T*p}{1000-25*p} \qquad \text{(for heating)} \qquad (3.4)$$

$$Cost = -\frac{100*\Delta T*p}{1000-25*p} \qquad \text{(for cooling)} \qquad (3.5)$$

3.3 Testing scenarios

In order to test the MAS in the test room, several experiments are run. These experiments are based on scenarios of regular workdays in offices. For the experiments the following cases are considered:

- Two person profiles, i.e. an energy waster and an energy saver. The energy wasting occupant does not care about high energy consumptions and the energy conscious occupant tries to keep the energy consumption at a minimum
- Two weather profiles, i.e. a clouded winter day and a clear summer day. During the winter days heating is taken into account but cooling is not and during the summer days cooling is taken into account and heating is not.
- Four control approaches, i.e. one manual control and three different MAS control approaches. The manual control is based on the thermostat approach where occupants set the desired temperature manually. This method is used in most buildings [Davidsson and Boman, 2005]. The MAS control consists of cooperating agents that control both the temperature and lighting in the room automatically. The agents' temperature setpoint is based on the preferred temperature of the occupant that is present in the room.

In total there are 16 possible combinations with these cases, which are all shown in table 4.

Table 4: The 16 scenarios that are tested. At the left side the different combinations of user and season profiles are described. The season and the user's preferred temperature are shown between brackets. At the top the different control approaches are described. The limitations of each control is shown between brackets. The various scenarios are numbered from 1.1 to 4.4. For example, scenario 1.1 stands for the measurement with the energy waster on a summer day with the user's preferred temperature being 27 °C and with manual control of the room where the blinds are always fully down and the energy price is 2 during the whole day.

Control approach / Person + season	Manual control (static blinds, static price)	MAS control (static blinds, static price)	MAS control (dynamic blinds, static price)	MAS control (dynamic blinds, dynamic price)
Energy waster (summer, T_{user} = 27 °C)	Scenario 1.1 Blinds = 0 Price = 2	Scenario 1.2 Blinds = 0 Price = 2	Scenario 1.3 Blinds = 0 Price = 2	Scenario 1.4 Blinds = 0 Price = 2
Energy waster (winter, T_{user} = 21 °C)	Scenario 2.1 Blinds = 0 Price = 2	Scenario 2.2 Blinds = 0 Price = 2	Scenario 2.3 Blinds = 0 Price = 2	Scenario 2.4 Blinds = 0 Price = 2
Energy saver (summer, T_{user} = 26 °C)	Scenario 3.1 Blinds = variable Price = 2	Scenario 3.2 Blinds = variable Price = 2	Scenario 3.3 Blinds = variable Price = 2	Scenario 3.4 Blinds = variable Price = 2
Energy saver (winter, T_{user} = 22 °C)	Scenario 4.1 Blinds = variable Price = variable	Scenario 4.2 Blinds = variable Price = variable	Scenario 4.3 Blinds = variable Price = variable	Scenario 4.4 Blinds = variable Price = variable

3.4 Measurement results

In this section the results of the experiments are presented. Figure 14 shows an example graph of experiment 1.1. All other graphs of the measurements can be found in appendix E. This graph shows the measurements of the five sensors. The top graph shows the lighting measurements, i.e. the indoor illuminance and the indoor luminance. The bottom graph shows the temperature measurements, i.e. the external temperature, inlet temperature and internal temperature. The white boxes with a red edge below the graphs show the operations on specific times.

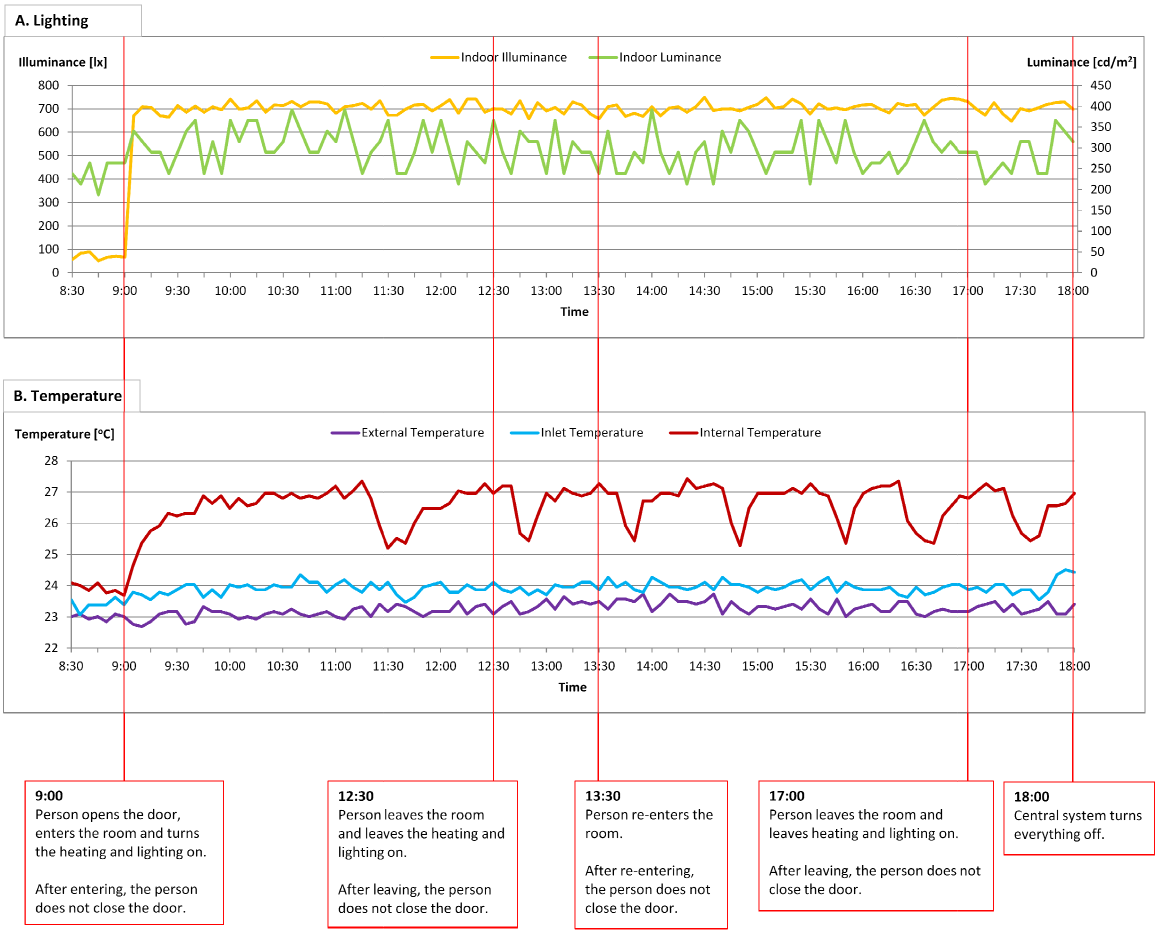


Figure 14: Results of experiment 1.1 (energy waster with manual control). This scenario represents a regular working day in winter. The person working in the room is someone who does not care about energy loads. The blinds are static and are always fully down. The person enters the room at 9:00, turns the lights on and sets the thermostat to 27 °C. He never turns the lighting or heating off, even not when he leaves for home at 17:00. The central system automatically turns the heating and lighting off at 18:00.

In order to compare the results of the different scenarios, these results are put together in tables. These tables are divided per person and season, where each table represents one of the two person profiles on either a summer day or a winter day (see tables 5 to 8). Since the external temperature of the room, which equals the temperature inside the laboratory, cannot be controlled by the MAS and is always around 24 °C, a summer day is represented by setting the user's preferred temperature to 26 or 27 °C and a winter day is represented by setting the user's preferred temperature to 21 or 22 °C.

Table 5: Results of the energy waster on a winter day. This table shows the time that the internal temperature deviates from the user's preferred temperature, the energy loads and also the experiment number and where the graphs of these experiments can be found.

Energy waster (T_{user} = 27 ^{o}C)	Temperature in the room (during the period that someone is present)	Energy loads	Experiment
Manual control	Below 26 ^{o}C: 70 minutes Below 25 ^{o}C: 5 minutes	Heating: 9,17 kWh Lighting: 2,07 kWh	Scenario 1.1 (see appendix A, figure E-1 and E-1a)
MAS control 1 (static blinds, static price)	Below 26 ^{o}C: 210 minutes Below 25 ^{o}C: 20 minutes	Heating: 3,88 kWh Lighting: 1,61 kWh	Scenario 1.2 (see appendix A, figure E-2 and E-2a)
MAS control 2 (dynamic blinds, static price)	Below 26 ^{o}C: 10 minutes Below 25 ^{o}C: 5 minutes	Heating: 4,25 kWh Lighting: 0,81 kWh	Scenario 1.3 (see appendix A, figure E-3 and E-3a)
MAS control 3 (dynamic blinds, dynamic price)	Morning (price = 2) Below 26 ^{o}C: 10 minutes Below 25 ^{o}C: 0 minutes Afternoon (price = 4) Below 26 ^{o}C: 20 minutes Below 25 ^{o}C: 0 minutes	Heating: 3,29 kWh Lighting: 0,75 kWh	Scenario 1.4 (see appendix A, figure E-4 and E-4a)

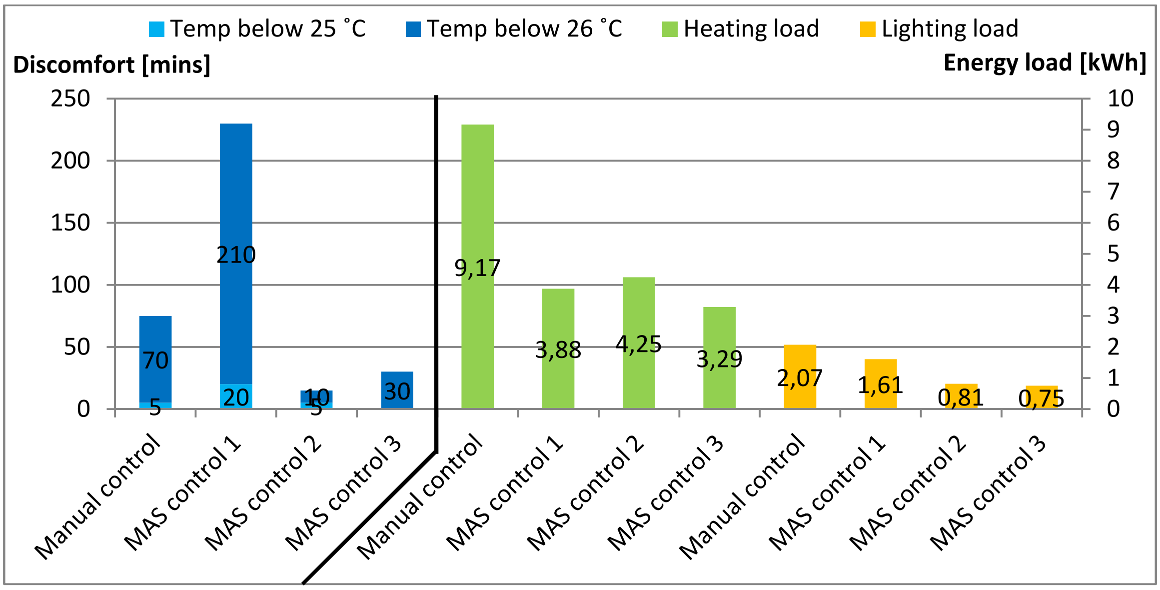


Figure 15: Graphical representation of table 5

Table 6: Results of the energy waster on a summer day. This table shows the time that the internal temperature deviates from the user's preferred temperature, the energy loads and also the experiment number and where the graphs of these experiments can be found.

Energy waster (T_{user} = 21 °C)	**Temperature in the room** (during the period that someone is present)	**Energy loads**	**Experiment**
Manual control	Above 22 °C: 100 minutes Above 23 °C: 15 minutes	Cooling: 45,9 kWh Lighting: 2,07 kWh	Scenario 2.1 (see appendix A, figure E-5 and E-5a)
MAS control 1 (static blinds, static price)	Above 22 °C: 295 minutes Above 23 °C: 85 minutes	Cooling: 27,6 kWh Lighting: 1,61 kWh	Scenario 2.2 (see appendix A, figure E-6 and E-6a)
MAS control 2 (dynamic blinds, static price)	Above 22 °C: 185 minutes Above 23 °C: 65 minutes	Cooling: 35,7 kWh Lighting: 1,60 kWh	Scenario 2.3 (see appendix A, figure E-7 and E-7a)
MAS control 3 (dynamic blinds, dynamic price)	<u>Morning (price = 2)</u> Above 22 °C: 85 minutes Above 23 °C: 20 minutes <u>Afternoon (price = 4)</u> Above 22 °C: 95 minutes Above 23 °C: 10 minutes	Cooling: 29,2 kWh Lighting: 1,43 kWh	Scenario 2.4 (see appendix A, figure E-8 and E-8a)

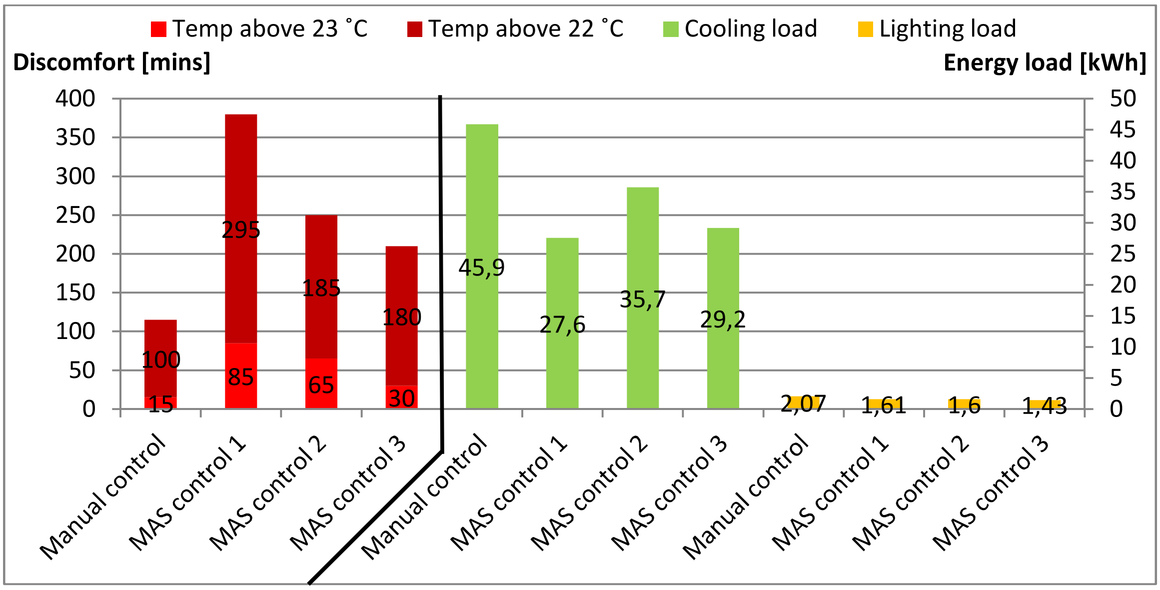


Figure 16: Graphical representation of table 6

Table 7: Results of the energy saver on a winter day. This table shows the time that the internal temperature deviates from the user's preferred temperature, the energy loads and also the experiment number and where the graphs of these experiments can be found.

Energy saver (T_{user} = 26 °C)	Temperature in the room (during the period that someone is present)	Energy loads	Experiment
Manual control	Below 25 °C: 10 minutes Below 24 °C: 0 minutes	Heating: 4,35 kWh Lighting: 1,61 kWh	Scenario 3.1 (see appendix A, figure E-9 and E-9a)
MAS control 1 (static blinds, static price)	Below 25 °C: 0 minutes Below 24 °C: 0 minutes	Heating: 0 kWh Lighting: 1,61 kWh	Scenario 3.2 (see appendix A, figure E-10 and E-10a)
MAS control 2 (dynamic blinds, static price)	Below 25 °C: 0 minutes Below 24 °C: 0 minutes	Heating: 1,98 kWh Lighting: 0,77 kWh	Scenario 3.3 (see appendix A, figure E-11 and E-11a)
MAS control 3 (dynamic blinds, dynamic price)	Morning (price = 2) Below 25 °C: 10 minutes Below 24 °C: 0 minutes Afternoon (price = 4) Below 25 °C: 40 minutes Below 24 °C: 0 minutes	Heating: 2,29 kWh Lighting: 0,80 kWh	Scenario 3.4 (see appendix A, figure E-12 and E-12a)

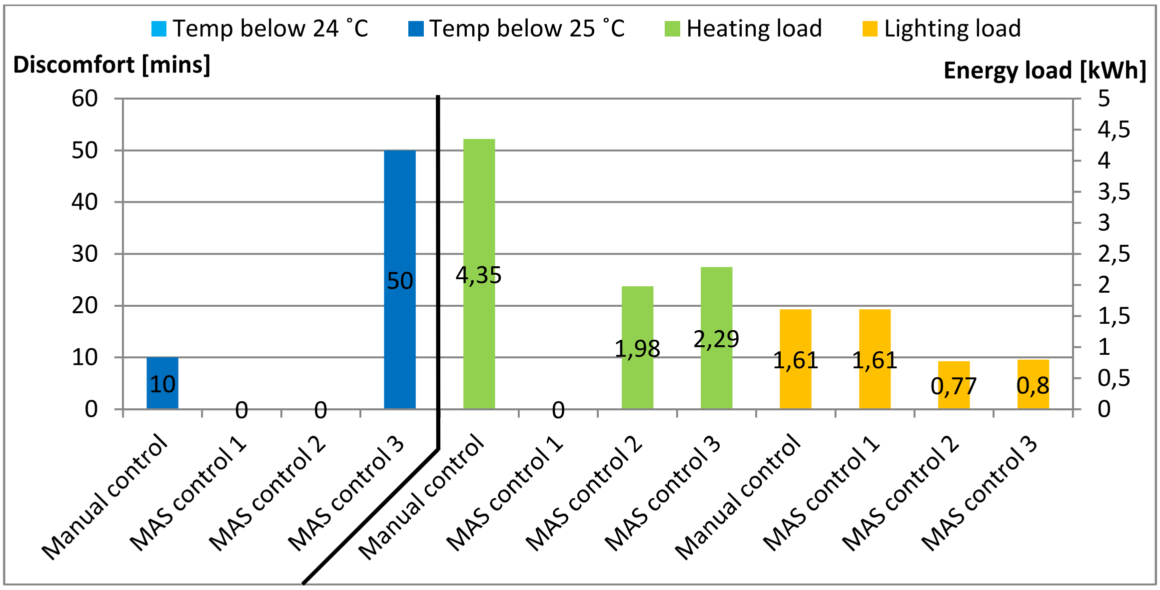


Figure 17: Graphical representation of table 7

Table 8: Results of the energy saver on a summer day. This table shows the time that the internal temperature deviates from the user's preferred temperature, the energy loads and also the experiment number and where the graphs of these experiments can be found.

Energy saver (T_{user} = 22 °C)	Temperature in the room (during the period that someone is present)	Energy loads	Experiment
Manual control	Above 23 °C: 35 minutes Above 24 °C: 5 minutes	Cooling: 24,3 kWh Lighting: 1,61 kWh	Scenario 4.1 (see appendix A, figure E-13 and E-13a)
MAS control 1 (static blinds, static price)	Above 23 °C: 225 minutes Above 24 °C: 195 minutes	Cooling: 35,7 kWh Lighting: 1,61 kWh	Scenario 4.2 (see appendix A, figure E-14 and E-14a)
MAS control 2 (dynamic blinds, static price)	Above 23 °C: 140 minutes Above 24 °C: 90 minutes	Cooling: 14,4 kWh Lighting: 1,54 kWh	Scenario 4.3 (see appendix A, figure E-15 and E-15a)
MAS control 3 (dynamic blinds, dynamic price)	Morning (price = 2) Above 23 °C: 20 minutes Above 24 °C: 10 minutes Afternoon (price = 4) Above 23 °C: 105 minutes Above 24 °C: 0 minutes	Cooling: 23,5 kWh Lighting: 1,24 kWh	Scenario 4.4 (see appendix A, figure E-16 and E-16a)

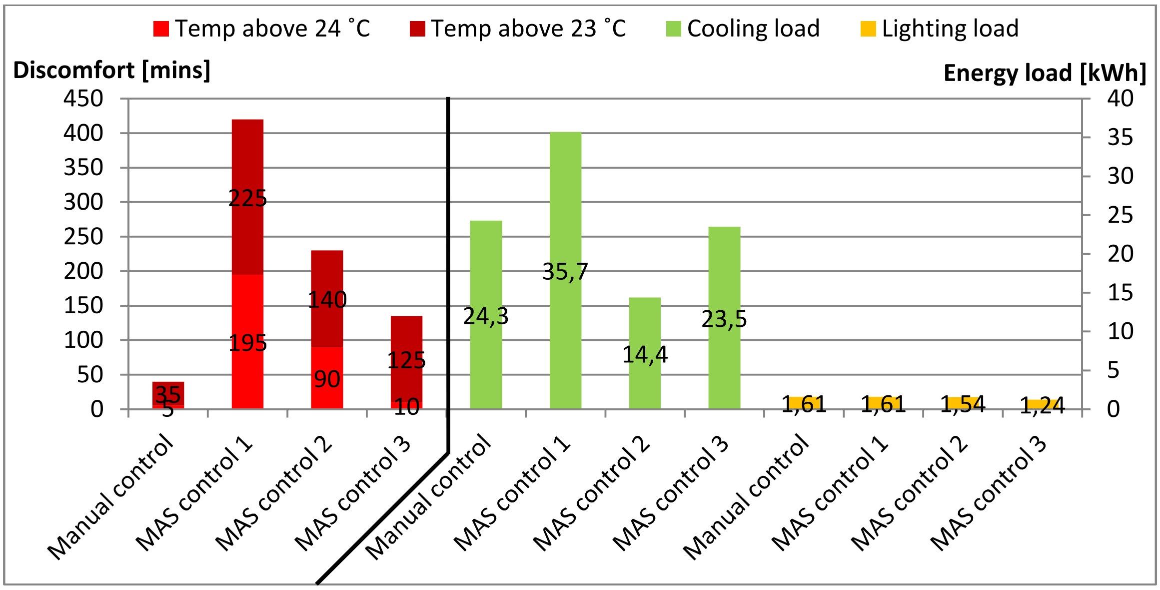


Figure 18: Graphical representation of table 8

3.5 Discussion of the results

This section discusses the measurement results. The discussions, four in total, are sorted per combination of user profile and season. At the end there are some general remarks on the measurement results.

<u>Results Scenario 1.1 to 1.4</u>

Regarding the comfort, “MAS control 1” results into more discomfort than the manual control. This seems weird at first, but is explained by the fact that the energy price is set to 4 during the “MAS control 1” experiment. This leads to the Room agent instructing the Heating agent to lower the thermostat from 27 ^{o}C to 26 ^{o}C, which automatically leads to lower temperatures. The energy price is set to 2 for “MAS control 2” and “MAS control 3”, as a result of which the Room agent does not instruct the Heating agent anymore to set the thermostat lower than the user’s preferred temperature and consequently the discomfort decreases.

The energy loads of the MAS approaches are lower than that of the manual control. With MAS control the energy saving for heating almost reaches up to 60% and with “MAS control 3” the energy saving even rises to 64%. The MAS control also saves energy on lighting, decreasing the energy use with 22% with static blinds (when the blinds are fully down) and with dynamic blinds this energy saving even reaches up to 62%. Dynamic blinds also have another benefit, which is the increase in visual comfort because natural lighting enters the room. The time that the temperature deviates from the user’s preferred temperature decreases significantly in the case of dynamic blinds.

<u>Results Scenario 2.1 to 2.4</u>

Regarding the comfort, “MAS control 1” again results into more discomfort than the manual control. The reason for this is the same as with scenario 1.2, namely the fact that the energy price is set to 4 during the “MAS control 1” experiment. This leads to the Room agent instructing the Cooling agent to raise the temperature setpoint from 21 ^{o}C to 22 ^{o}C, which automatically leads to higher temperatures. The energy price is set to 2 for “MAS control 2” and “MAS control 3”, as a result of which the Room agent does not instruct the Cooling agent anymore to set the temperature setpoint higher than the user’s preferred temperature and consequently the discomfort decreases.

The energy loads of the MAS approaches are lower than that of the manual control. With MAS control the energy saving for cooling almost reaches up to 36% with “MAS control 3”. Although the energy saving is even higher with “MAS control 1”, this control approach is not taken into consideration because the temperature setpoint for this control approach was set to 22 ^{o}C instead of 21 ^{o}C. The MAS control also saves energy on lighting, decreasing the energy use with 22% with “MAS control 1” and “MAS control 2” and with “MAS control 3” this energy saving even reaches up to 31%. This 9% difference is not caused by the fact that the blinds are static or dynamic, but by the fact that the energy price of “MAS control 3” rises to 4 in the afternoon. Because of this price change the temperature setpoint raised from 21 ^{o}C to 22 ^{o}C and as a result the cooling is turned off a couple of times in the afternoon. And when the cooling is turned off, the Lighting agent is allowed to raise the blinds and as a result the lighting is turned off. However, when the blinds are raised, the temperature in the room rises and as a result the cooling is turned on and the blinds are lowered again.

<u>Results Scenario 3.1 to 3.4</u>

Regarding the comfort, there are no big differences. The only significant difference between the control approaches is the fact that “MAS control 3” shows relatively much discomfort in the afternoon. But this is explained by the fact that the energy price rises to 4 in the afternoon. Because of this price change the temperature setpoint dropped from 26 ^{o}C to 25 ^{o}C and as a result the temperature drops below 25 ^{o}C more often in the afternoon.

The energy loads of the MAS approaches are lower than that of the manual control. With MAS control, the energy saving for heating reaches up to 47% with “MAS control 3”. Although the energy saving is even higher with “MAS control 1” and “MAS control 2”, these control approaches are not taken into consideration because the external temperature was 26 ^{o}C and 24 ^{o}C, respectively, whilst the external temperature was 23 ^{o}C during the experiment with manual control. The high external temperature is also the reason why “MAS control 1” does not need any heating at all. The MAS control also saves energy on lighting, decreasing the energy use with 50-52% with dynamic blinds.`

<u>Results Scenario 4.1 to 4.4</u>
Regarding the comfort, all three MAS controls result into more discomfort than the manual control. During the experiment of “MAS control 1” the external temperature was 25,5 ^{o}C, instead of 23 ^{o}C. Because of this high external temperature, the chiller was not able to cool down the internal temperature from 27 ^{o}C to 22 ^{o}C. During the experiment of “MAS control 2” something strange happened with the cooling in the afternoon. Although the Cooling agent gave instructions to turn the cooling on, this apparently did not happen. This error led to high internal temperature in the afternoon. During the experiment of “MAS control 3” the external temperature was slightly higher than during the manual control experiment and also the energy price rose from 2 to 4 in the afternoon. . Because of this price change the temperature setpoint rose from 22 ^{o}C to 23 ^{o}C and as a result the temperature rises above 25 ^{o}C more often in the afternoon.

The energy loads are difficult to compare because during the experiment of “MAS control 1” the external temperature was higher than during the three other experiments and during the experiment of “MAS control 2” the cooling did not work properly in the afternoon. Only the results of the “MAS control 3” approach are suitable for comparison. The cooling loads do not differ very much, but the lighting loads decrease with 23%. This difference is mainly caused by the effects of dynamic blinds. With the manual control the blinds are always fully down, while the dynamic blinds of “MAS control 3” provide natural lighting.

<u>Comparing these results with results from literature</u>
The study of Davidsson and Boman [Davidsson, 2005] concluded that the energy saving for heating and cooling can go up to almost 40%. In this thesis the energy saving percentages for heating are even higher and go up to almost 65%. This can be explained by the fact that heat from the sunlight is used as an alternative for heat from the radiator. Whenever the sun provides enough heat, the radiator is not needed.

For cooling this energy saving percentage is slightly lower, specifically 36%. However, this percentage is based on a measurement where the energy price rises in the afternoon and consequently the comfort level drops. So if the price would not have changed, this percentage will be lower.

The study of Mahdavi et al. [Mahdavi, 2008] concluded that the energy saving for lighting can possibly reach up to 70%. In this thesis the energy saving percentage for lighting reaches 62%. However, the results of the study of Mahdavi are based on calculations on the basis of observations, while the results of this thesis are based on real-time measurements. Also the methods used for energy saving are different. Mahdavi used two energy saving methods. In the first method, the lights are automatically switched off after 10 minutes if the office is not occupied. In this thesis the lights are immediately switched off if there is no one present in the room. The second method uses an automated dimming principle, whereby the luminaires are dimmed down to maintain an illuminance level of 500 lx at the workstation. In the experiments of this thesis it was not possible to dim the lights, because it was only possible to turn the lights on or off.

Chapter 4 Conclusion, discussion and recommendations

This chapter describes the lessons learned from the experiments and the recommendations for future research. In section 4.1 the conclusions from this research are described. Section 4.2 discusses the test room and the measurements. Section 4.3 describes the recommendations on the building physics aspect, the control aspect and some general recommendations.

4.1 Conclusion

Although not all experiments went well and the daily variation of the external temperature affected the outcome of some results, the experiments do come up to the general expectations of the MAS. Table 9 shows the expected results of each scenario.

Table 9: Expected behavior of the different control approaches

Scenario	Control approach	Expected behavior
Scenario 1.1	Manual control	Heating and lighting are on even when no one is present in the room
Scenario 1.2	MAS control (static blinds, static price)	Heating and lighting are off when there is no one in the room
Scenario 1.3	MAS control (dynamic blinds, static price)	Less artificial lighting is needed because natural lighting is utilized and also lower heating loads are expected because the sunlight also provides additional heating
Scenario 1.4	MAS control (dynamic blinds, dynamic price)	Lower internal temperature and lower heating loads in the afternoon
Scenario 2.1	Manual control	Cooling and lighting are on even when no one is present in the room
Scenario 2.2	MAS control (static blinds, static price)	Cooling and lighting are off when there is no one in the room
Scenario 2.3	MAS control (dynamic blinds, static price)	Only when cooling is off, less artificial lighting is needed because natural lighting is utilized. When cooling is on, nothing changes.
Scenario 2.4	MAS control (dynamic blinds, dynamic price)	Higher internal temperature and lower cooling loads in the afternoon
Scenario 3.1	Manual control	Heating and lighting are off when there is no one in the room
Scenario 3.2	MAS control (static blinds, static price)	Nothing changes compared to scenario 3.1
Scenario 3.3	MAS control (dynamic blinds, static price)	Less artificial lighting is needed because natural lighting is utilized and also lower heating loads are expected because the sunlight also provides additional heating
Scenario 3.4	MAS control (dynamic blinds, dynamic price)	Lower internal temperature and lower heating loads in the afternoon
Scenario 4.1	Manual control	Cooling and lighting are off when there is no one in the room
Scenario 4.2	MAS control (static blinds, static price)	Nothing changes compared to scenario 4.1
Scenario 4.3	MAS control (dynamic blinds, static price)	Only when cooling is off, less artificial lighting is needed because natural lighting is utilized. When cooling is on, nothing changes.
Scenario 4.4	MAS control (dynamic blinds, dynamic price)	Higher internal temperature and lower cooling loads in the afternoon

4.2 Discussion

The discussion is divided into two parts. The first part describes the constraints of the test room and the second part presents the discussion on the measurements.

Constraints of the test room

The test room that has been used for the experiments had its advantages, but also had some constraints. These constraints are:

- The door could not be fully opened. The device that was used to open and close the door was only able to open the door partially. When 'fully' opened, this opening was just big enough for a person to walk through.
- The door also could not be fully closed. When the device closed the door, it was always left ajar. This crack caused air leakage.
- There was no window in the test room. This means that it was not possible for the (simulated) user to open or close a window.
- The insulation of the test room was very bad. This caused the temperature inside the room to drop very fast when the heating was turned off and the temperature rose very fast when the cooling was turned off.
- The outside temperature was not controllable. Since the test room was situated inside a laboratory the outside temperature was basically the internal temperature of the lab. This temperature fluctuated depending on the weather outside. On rainy days the temperature was around 23 ^{o}C and on warm sunny days the temperature could reach 26 ^{o}C.
- The supply of ventilation air was set to 237 m^3/h and the exhaust of ventilation air was set to 118 m^3/h. The reason why the amount of supply air is double the amount of exhaust air is because the room insulation was very bad and the door could not be fully closed, as has been mentioned before. This extra amount of supply air compensated for the temperature losses.
- The luminance and illuminance of the light panel, which mimicked the sunlight, could not be controlled separately. Because of this a choice had to be made whether the light panel should be based on either the illuminance profile of the sun or the luminance profile of the sun. Since the sunlight measurement data[3] provided illuminance profiles of both a sunny day and a clouded day and the luminance profile was only available for the sunny day, and besides it was also more difficult to make this luminance data suited for the experiments, a choice is made to use the illuminance profiles instead of the luminance profiles.
- The light panel, which mimicked the sunlight, only had six levels of brightness. Because of this the illuminance profile of the sun had to be scaled into six parts. So it was not possible to gradually increase or decrease the amount of sunlight.

Discussion on the measurements

This section explains the choices that have been made regarding the experiments and also elaborates on the results of the measurements. Some discussion points are:

- The reason for choosing a test room instead of a real room is mainly because of the fact that the first option provides the possibility to create specific sunlight profiles. These profiles can represent certain weather types, e.g. a clouded day or a sunny day, and more importantly these profiles are exactly the same for every experiment. Consequently the results are better comparable with one another.
- The sensors that measures the internal temperature in the room is placed directly below the air inlet. The reason for this is that the insulation in the test room is very bad and as a results of which it was impossible to cool down the room when this temperature sensor was placed elsewhere in the room. The disadvantage however of choosing this spot for the sensor is that the comfort at that place is very bad because of the strong airflows. But since airflows are

[3] Sunlight measurement data is the data that is provided by dr. ir. Myriam Aries.

beyond the scope of this thesis, this comfort aspect was not taken into account for the experiments.

- The energy savings of the MAS control will be even higher when the person in the room would leave the room temporarily more frequently. For example when the person has a meeting elsewhere or when the person only works in the morning and is free in the afternoon. In these cases the manual control will still heat up (or cool down) the room when the person is absent while the MAS control turns the heating (or cooling) off when there is no one present.
- The lights are automatically turned on or off depending on the indoor illuminance. The measurements have shown that the lights are sometimes switched on and off after 5 minutes. This may cause discomfort to the person in the room.
- The utility function of the room agent is not per definition the most ideal for any office room in any building, but is purely designed for the experiments. Every building manager has the possibility to change the utility function to his own preferences. It is even possible to assign a different utility function to every room.
- Instead of using utility functions, it is also a possibility to let the agents negotiate with one another in order to accomplish an objective. For instance, when the heating agent wants to heat up the room and the room agent does not want that to happen because the price of energy is very high, these two agents can negotiate with each other and whichever agent offers the most (virtual money) gets what it wants.

4.3 Recommendations

The recommendations are divided into two parts. The first part describes the recommendations in the field of building physics of the experiments and the second part describes the recommendations on the control part.

Recommendations on building physics

The experiments have been executed in a test room situated in a laboratory. Although there are definitely advantages when running experiments in a test room, this test room also had its limitations. Some possible improvements for further research are:

- Use a test room with proper insulation. The insulation of the test room that has been used for the experiments was very bad and not realistic at all. If a room with better insulation is used the results would be more accurate.
- Include relative humidity and airflows. Relative humidity and airflows have been fully left out of this research, but these are important aspects to measure comfort. The sensor that measured the internal temperature was placed right below the air inlet. So even if this sensor indicates that the temperature is satisfactory, it does not mean that the relative humidity and airflows are also acceptable.
- Make use of equipment that can be gradually turned higher or lower. The equipment used for the experiments, i.e. radiator, chiller and luminaires, could only be turned on or off. Incremental changes were not possible for these equipment. But when incremental changes are possible, it gives agents an extra possibility to save energy.
- Use a real office room for the experiments. When using a real room the sunlight does not have to be simulated. This does not only make it a lot easier in software coding perspective, but also leads to more accurate results, in terms of heating load from the sun, outdoor luminance and outdoor illuminance. Another benefit of using a real room is the fact that a window can be opened and closed. This window can be used as an alternative for cooling when the external temperature is lower than the internal temperature.

- Control multiple rooms situated in the same corridor. This scenario can mimic a situation where the centralized system heats up the corridor while at the same time some users are individually cooling down their offices. This example presents a very interesting situation where communication between the “Corridor agent” and the Room agents is crucial. Good communication and cooperation between these agents can prevent situations like this to happen.

Recommendations on the control

The MAS in this report only consists of four agents, i.e. a Heating agent, a Cooling agent, a Lighting agent and a Room agent. Although these four agents are already capable to reduce the energy loads, more agents can be added to even further improve the performance of the MAS. Some examples are:

- Weather forecast agent, which can predict the weather and thereby gives the MAS the ability to anticipate on changes in weather, e.g. lowering the heating in advance when a lot of sun is expected.
- Energy market agent, which can predict the price of energy. If there is a good chance that the energy prices will drop, it could be sensible to temporarily lower the energy use until the prices have dropped.
- Energy storage agent, which controls an energy storage system. During the periods of low energy demand, all the extra available energy can be stored for future use. However, the requirement for such an agent is that an energy storage system must be available otherwise this agent is useless. An example of an energy storage system is an aquifer.

Another possibility to improve the performance of the MAS is to improve the current four agents. These four agents are very basic and a lot of features can be implemented to improve the agents. Some examples are:

- There is already a utility function for heating and cooling, but it is also possible to implement a utility function for lighting. This utility function would indicate to what extent blinds can be raised or lowered. In the current MAS the blinds are automatically fully lowered when the cooling is on. However, when the occupant of the room would like to always have (some) natural lighting in his room, it is worth considering whether the blinds should be partially opened, even if this leads to extra cooling loads. The same applies to the heating loads problem. When the sun shines during winter, the blinds are regulated in such a way that there is no glare for the person in the room. However, when the energy price is very high it may be worth considering to raise the blinds a little bit and having more sunlight coming into the room in order to reduce the heating load. Even though this means that the visual comfort will drop. In both cases the utility function would be used as a decision mechanism for the Lighting agent.
- Make use of the electronic diaries of the occupants. When the MAS knows in advance at what times a person enters and leaves the room, the temperature in the room can be regulated before this person actually enters or leaves the room. This brings extra comfort for the occupant, because the room is already brought at its desired temperature when this person enters, and also saves energy, because the heating (or cooling) can be turned off before this person has actually left the room.
- Raise or lower the blinds when there is no one in the room. This method utilizes sunlight to heat up the room in winter. The biggest advantage is that glare plays no role because there is no one inside the room. During summer the blinds can be fully lowered when no one is present because it does not matter whether it is light or dark in the room.
- Make use of neural networks. This feature gives agents the ability to learn from past experiences. For instance, when a person likes to have extra lighting late in the afternoon to prevent drowsiness, the agents are able to automatically increase the illuminance in the room without having the person to adjust the blinds or luminaires by himself every day.

Besides improving the performance of the MAS, it is also possible to improve the user-friendliness of the MAS. The current version of the MAS is very rigid and does not allow any human interventions. Some examples of improving the user-friendliness of the MAS are:

- Make manual adjustments possible for the occupant. In the current situation, when the occupant wants it to be dark in the room and switches off the lights, the MAS will immediately turn the lights back on. This should not happen because it should always be possible for users to overrule the system, not the other way around. Although this is a very difficult subject because the benefit of using a MAS entirely disappears when a user can for instance open doors and windows when the heating is on, some sort of user control is definitely necessary.
- Make manual adjustments possible for the system administrator. When the system administrator detects that something goes wrong in a room it should be possible to intervene. At the moment the only way to intervene is by shutting down the MAS on the computer where the MAS is running. But a better solution would be the possibility to shut the MAS down from another computer. This would give system administrators the possibility to monitor the MAS and intervene if necessary from anywhere around the world.
- A useful addition for both the occupants and the system administrators is a GUI screen with practical information and command options. This screen would visualize the processes, give measurement data of the room and also makes it easier for the user to adjust certain parameters.

References

Ahlersten, K. (2008) *Essentials of Microeconomics*, London: Bookboon

Bellifemine, F., Caire, G., Trucco, T. and Rimassa, G. (2010) 'Jade Programmer's Guide'

Braubach, L., Pokahr, A. and Lamersdorf, W. (2005) 'Jadex: A BDI-Agent System Combining Middleware and Reasoning', in Klusch, M., Unland, R. and Calisti, M., (ed.) *Software Agent-Based Applications, Platforms and Development Kits*, Basel: Birkhäuser

Chen, K.-Y. and Chen, C.-J. (2010) 'Applying multi-agent technique in multi-section flexible manufacturing system', *Expert Systems with Applications*, vol. 37, pp. 7310-7318

Davidsson, P. and Boman, M. (2000) 'A Multi-Agent System for Controlling Intelligent Buildings'

Davidsson, P. and Boman, M. (2005) 'Distributed monitoring and control of office buildings by embedded agents', *Information Sciences*, vol. 171, pp. 293-307

Geer, D. (2005) 'Eclipse Becomes the Dominant Java IDE', *Computer*, vol. 38, no. 7, July, pp. 16-18

Kharseh, M., Altorkmany, L. and Nordell, B. (2011) 'Global warming's impact on the performance of GSHP', *Renewable energy*, vol. 36, pp. 1485-1491

Mahdavi, A., Mohammadi, A., Kabir, E. and Lambeva, L. (2008) 'Occupants' operation of lighting and shading systems in office buildings', *Journal of Building Performance Simulation*, vol. 1, no. 1, March, pp. 57-65

Pennings, L. (2009) *Multi Agent System to Optimize Comfort and Energyflows in the Built Environment*, Eindhoven: TU/e

Wan, K.K.W., Li, D.H.W., Liu, D. and Lam, J.C. (2011) 'Future trends of building heating and cooling loads and energy consumption in different climates', *Building and Environment*, vol. 46, pp. 223-234

Wang, F., Yang, M. and Yang, R. (2008) 'Simulation of Multi-Agent based Cybernetic Transportation System', *Simulation Modelling Practice and Theory*, vol. 16, pp. 1606-1614

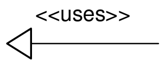
Wooldridge, M. (1999) 'Intelligent Agents', in Weiss, G., (ed.) *Multiagent Systems*, Cambridge: The MIT Press

World Bank, *Electric Power Consumption*, Available: http://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC/countries/NL-EU-US-Z4-ZJ?display=graph [6 Aug 2011]

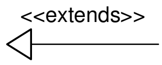
Appendix A

Use Case diagrams

In this appendix four use case diagrams are shown. A use case defines the interactions between one or more actors and the system to achieve a goal. Each actor has a task on its own and it uses several methods to complete this task. The interactions between the actors are illustrated by arrows. Two types of arrows are defined:



This arrow indicates that one actor makes use of functionalities of another actor



This arrow indicates the methods that are connected to an actor

The agents in the sequence diagrams are divided into two groups: simulation agents and MAS agents. The first are the agents that are needed for the experiments. These agents provide the input for the MAS agents. The latter are the agents that cooperatively control the temperature and lighting in the room.

The first use case diagram shows a simple overview of the four MAS agents. This diagram shows the task of each agent in the MAS and how the room agent makes use of the functionalities of the three other agents. The reason for the room agent to have this ability is to monitor the actions of the other agents and intervene when necessary.

The second use case diagram shows an extensive overview of the four MAS agents. This diagram does not only show the task of each agent and the interconnectivity between the agents, but also the methods that each agent has in order to accomplish its task.

The third use case diagram shows a simple overview of the four MAS agents and the three simulation agents. This diagram shows the task of every single agent and how the different agents are interrelated.

The fourth use case diagram shows an extensive overview of the four MAS agents and the three simulation agents. This diagram does not only show the task of each agent and the interconnectivity between the agents, but also the methods that each agent has in order to accomplish its task.

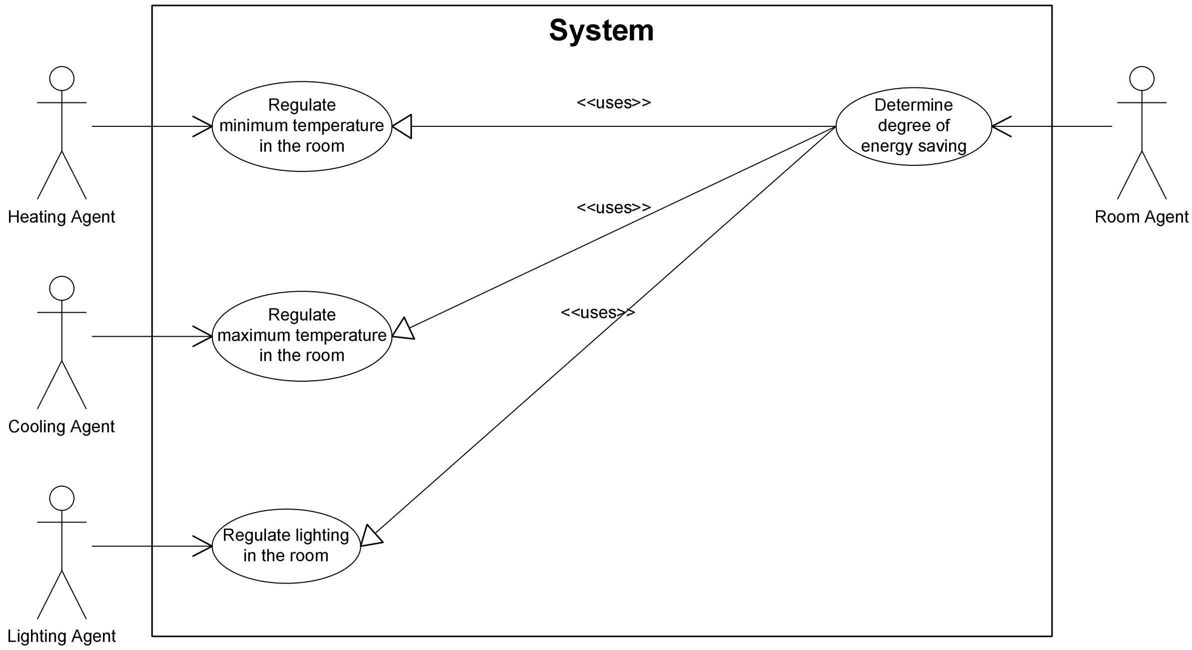


Figure A-1: MAS (simple version). This diagram shows the four agents that form the MAS. The heating agent and the cooling agent control the temperature and the lighting agent controls both the lighting and the blinds. The room agent records the price of energy and it can give instructions to the heating and cooling agent to respectively lower or raise the thermostat when the price of energy rises.

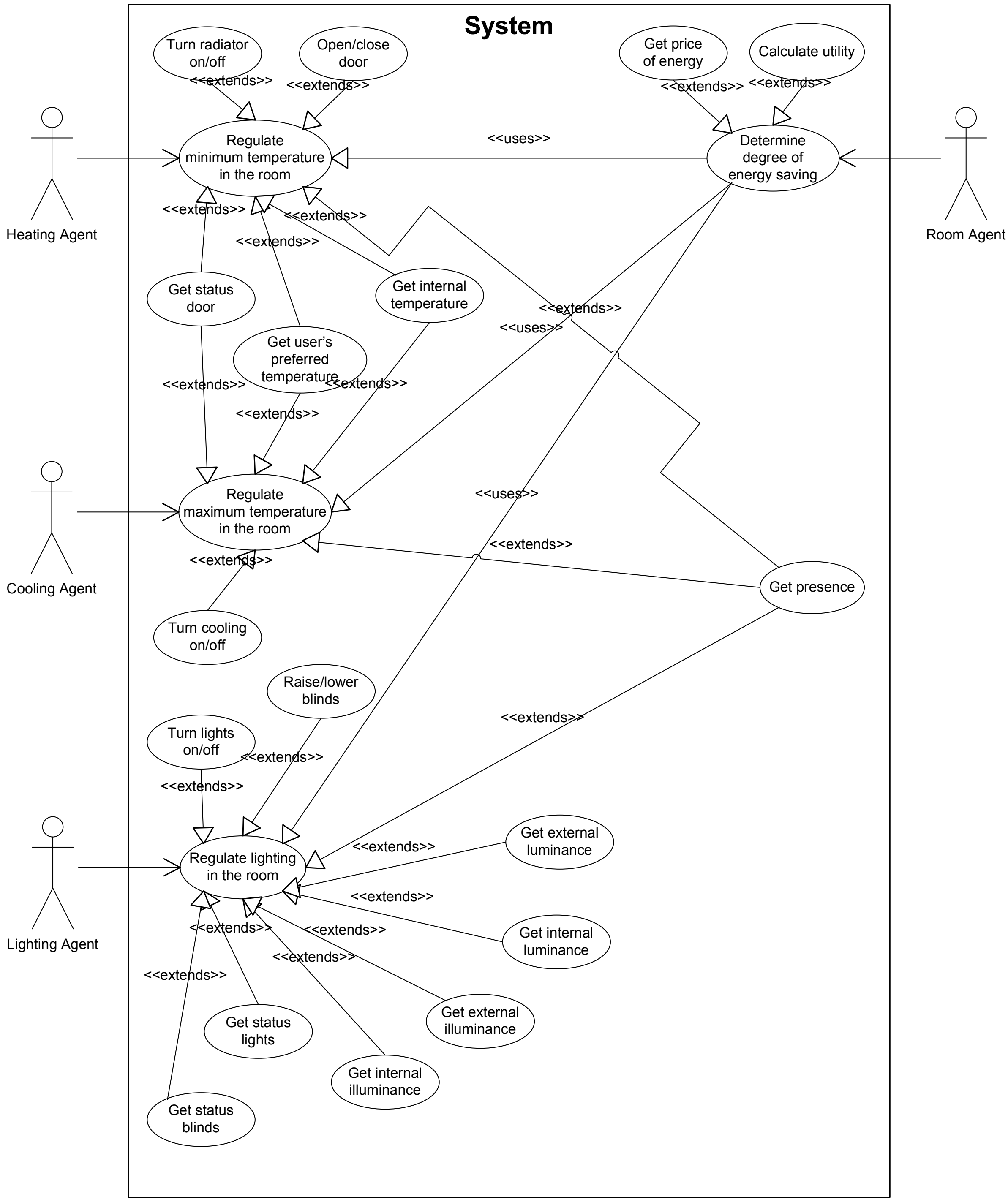


Figure A-2: MAS (extensive version). This diagram shows a detailed version of the four agents in the MAS. Every agent is provided with multiple methods in order to be able to execute its task.

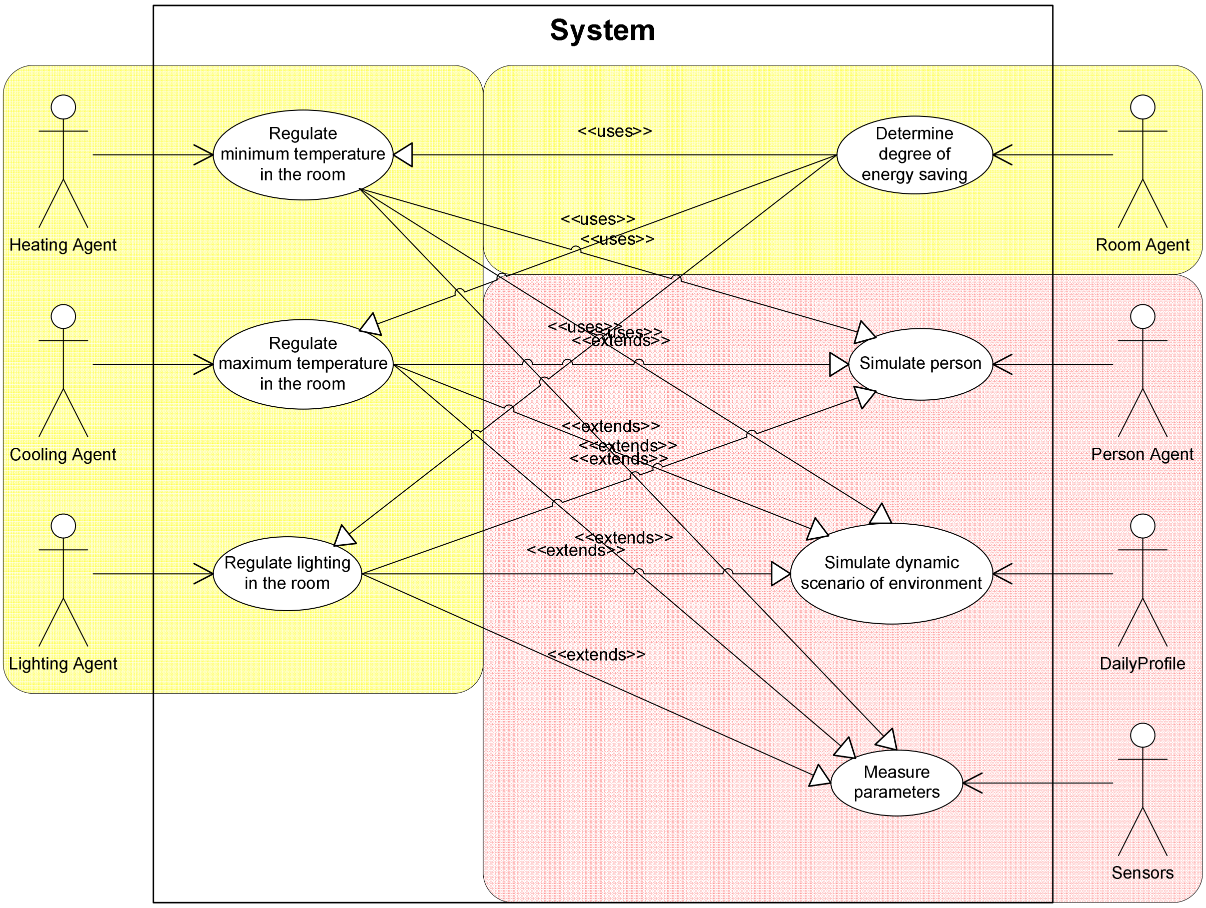


Figure A-3: MAS + simulation agents (simple version). This diagram shows all the agents that are needed for the MAS controlled experiments. The agents are separated into two groups: the MAS agents (yellow group) and the simulation agents (red group). The MAS agents control the temperature and lighting in the test room, while the simulation agents simulate specific scenarios.

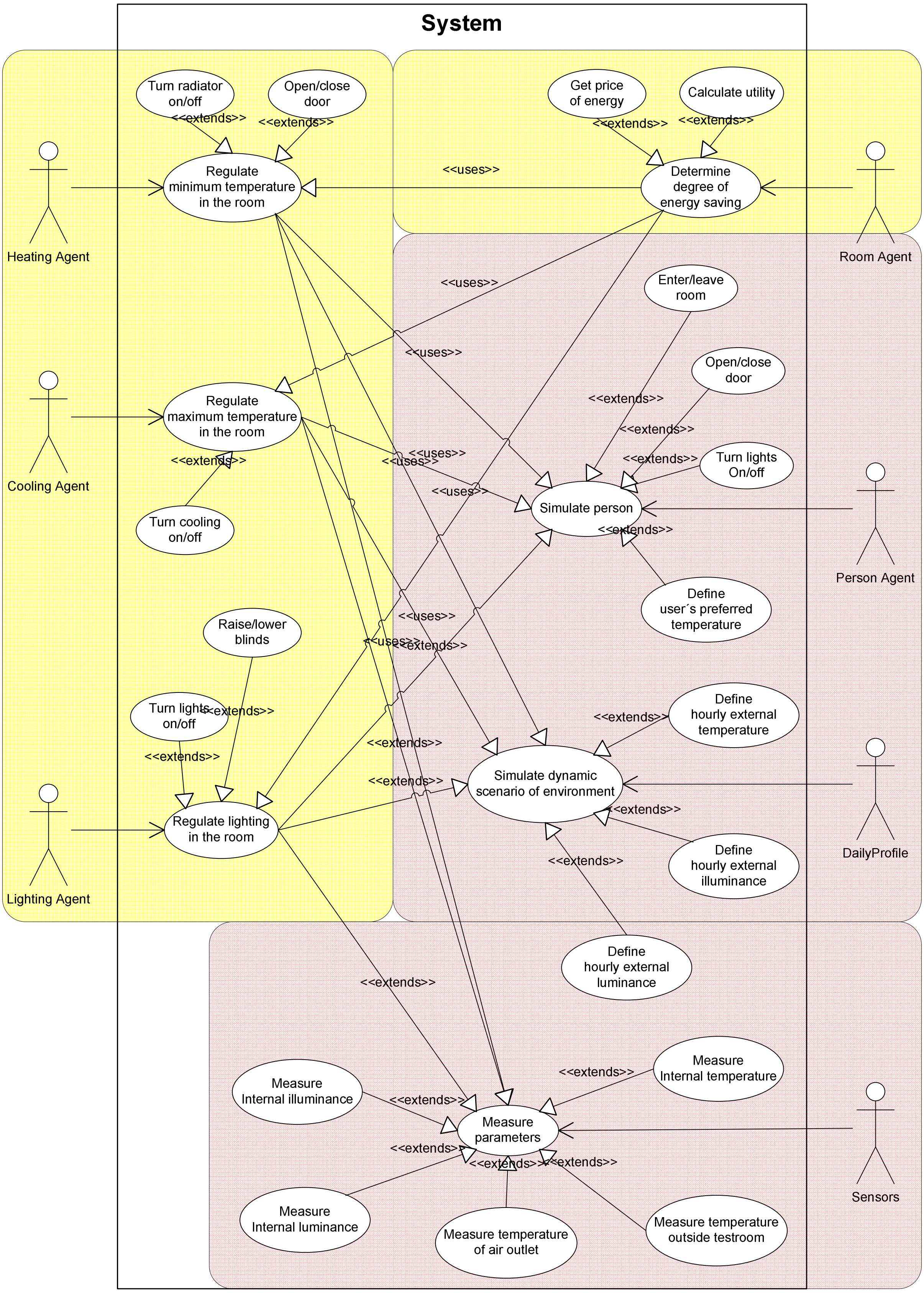


Figure A-4: MAS + simulation agents (extensive version). This diagram shows a detailed version of all the MAS agents (yellow group) and all the simulation agents (red group). Every agent is provided with multiple methods in order to be able to execute its task.

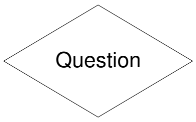
Appendix B

Activity diagrams

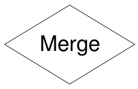
In this appendix four activity diagrams are shown to illustrate the workflow of the agents. Each activity diagram has one starting point and one endpoint. The endpoint does not so much mean that the agent terminates after that point, but rather means that the current process ends and a new process starts. Between the starting point and the endpoint the agent takes decisions based on its perception of the room. Arrows represent the order in which activities happen. The shape types used are:

 This black circle represents the start (initial state) of the workflow

 This encircled black circle represents the end (final state) of the workflow



This diamond represents a yes-no question



This diamond merges two arrows

This rounded rectangle represents an activity

These bars represent the start (split) or end (join) of concurrent activities

The first activity diagram shows the workflow of the heating agent. This agent controls the heating in the room and is able to close doors and windows. Before this agent can actually turn the heating on, it first needs to sends a request to the room agent for approval.

The second activity diagram shows the workflow of the cooling agent. This agent controls the cooling in the room and is also able to close doors and windows. Before this agent can actually turn the cooling on, it first needs to sends a request to the room agent for approval.

The third activity diagram shows the workflow of the lighting agent. This agent controls both the blinds and the lights. For the adjustments of the blinds and for turning the lights on, this agent needs to send a request to the room agent for approval.

The fourth activity diagram shows the workflow of the room agent. This agent waits for requests and responds to these.

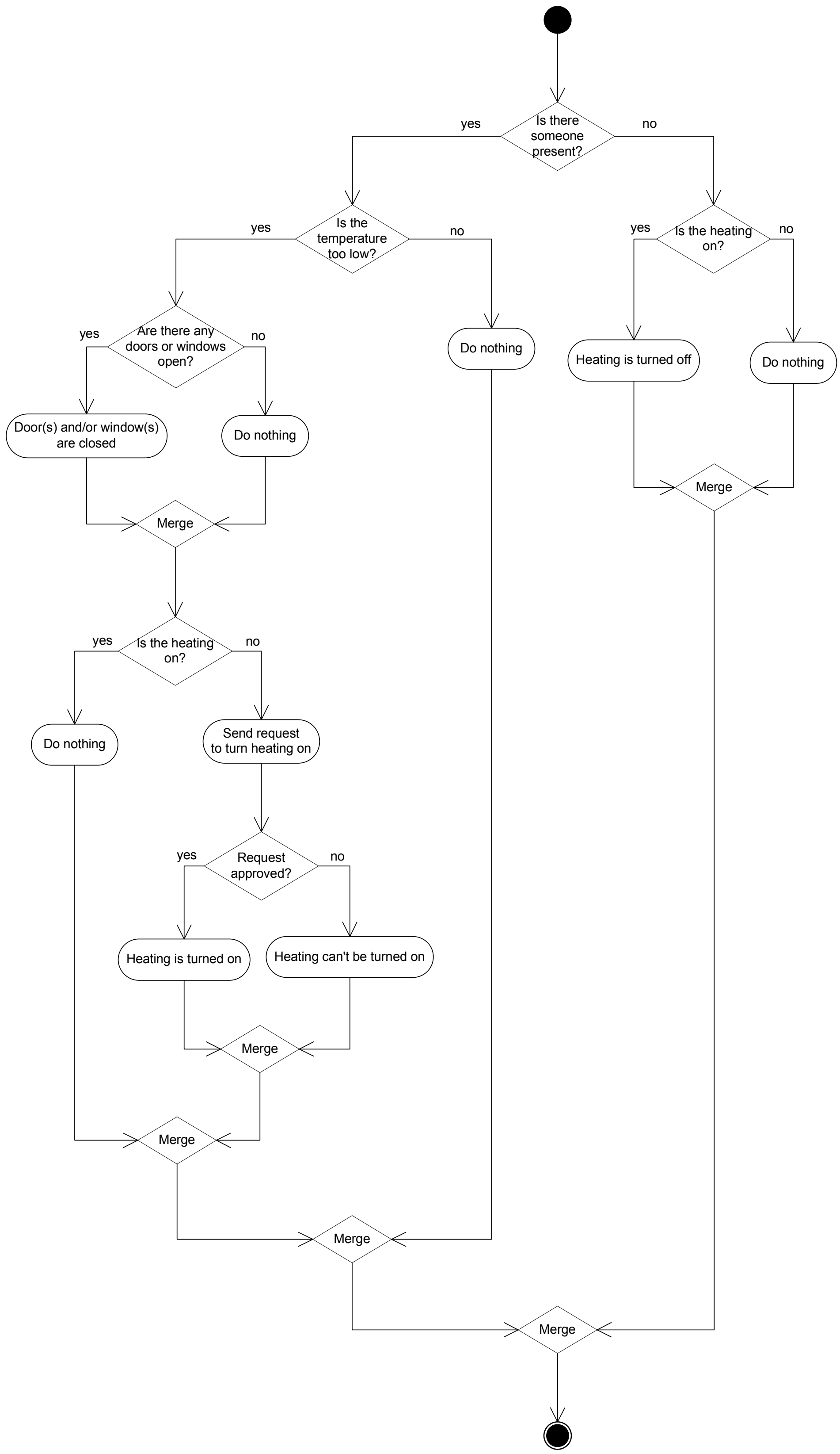


Figure B-1: Activity diagram of the heating agent. This diagram shows the flow of actions in the heating agent's workflow.

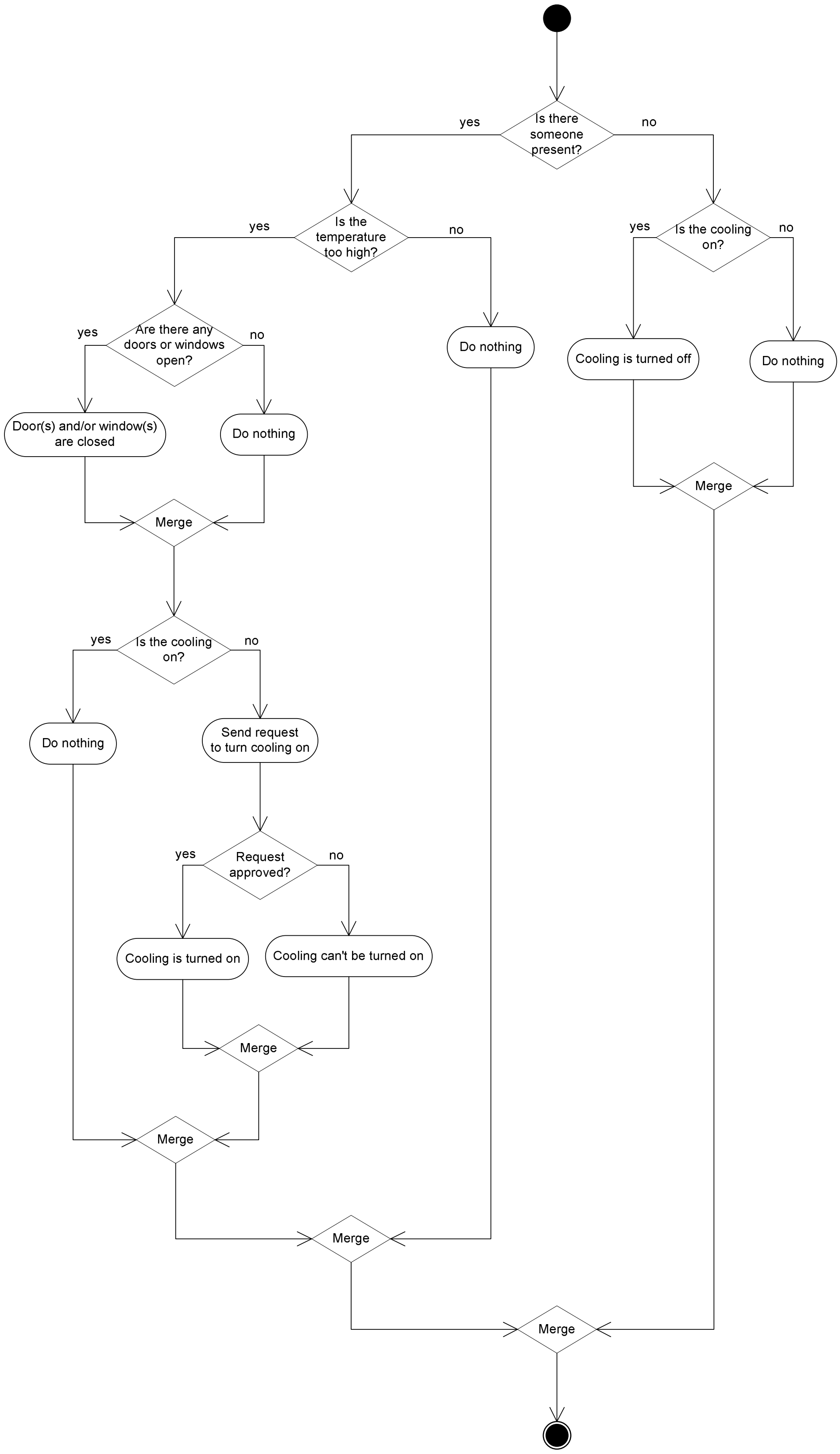


Figure B-2: Activity diagram of the cooling agent. This diagram shows the flow of actions in the cooling agent's workflow.

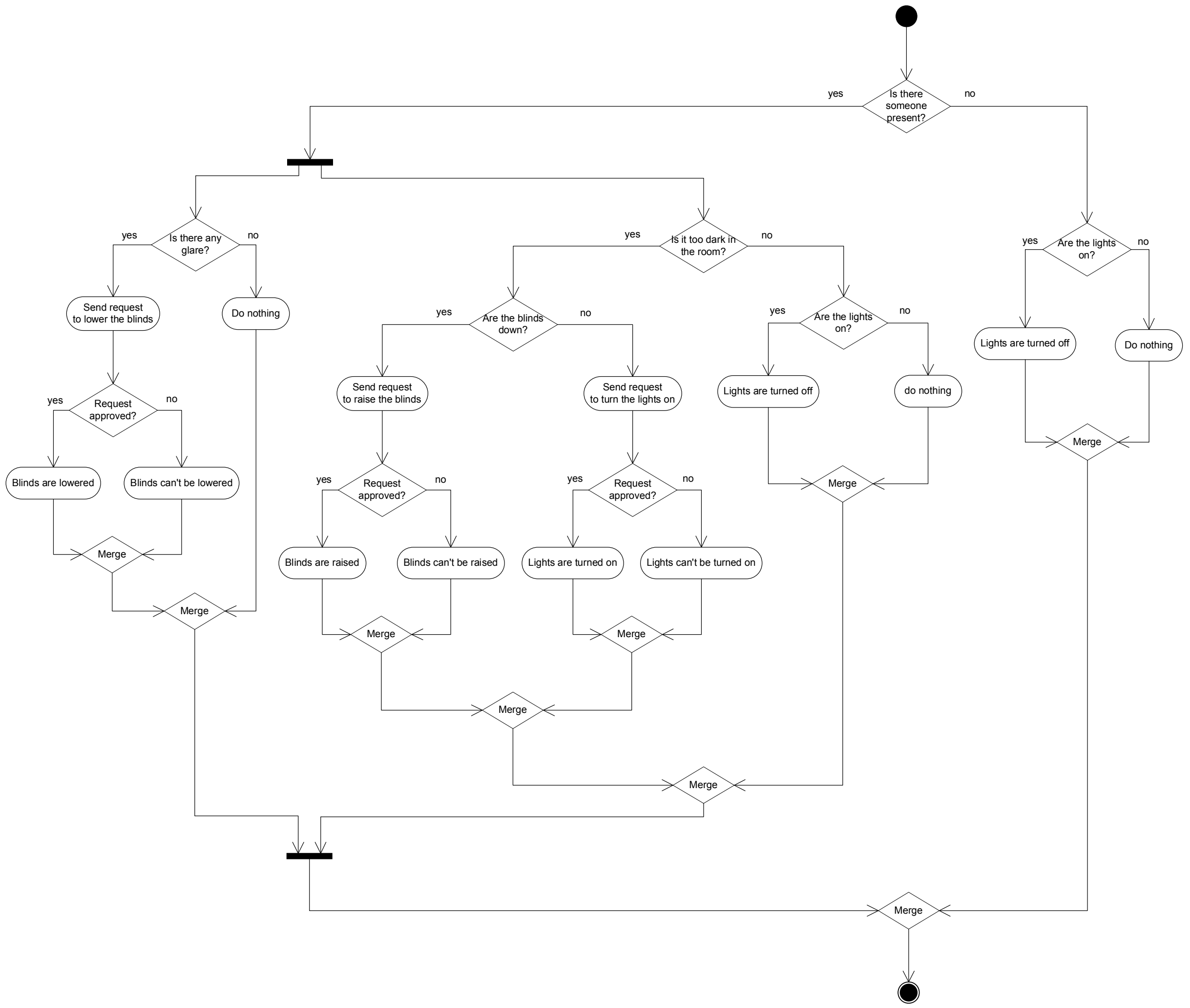


Figure B-3: Activity diagram of the lighting agent. This diagram shows the flow of actions in the lighting agent's workflow. When a person enters, the activities are split into two parallel sets of activities. One side takes care of the luminance and the other side takes care of the illuminance in the room.

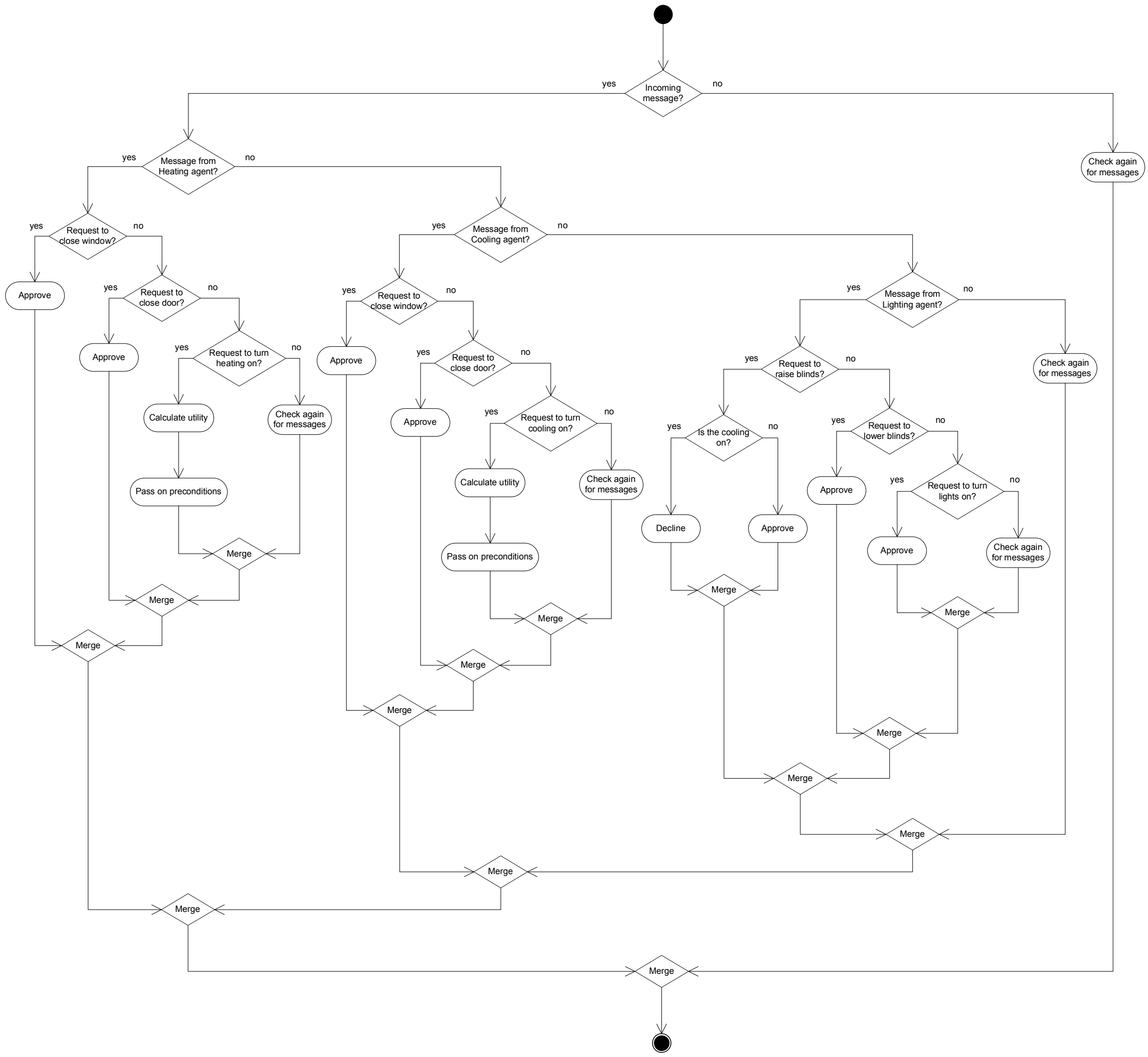


Figure B-4: Activity diagram of the room agent. This diagram shows the flow of actions in the room agent's workflow.

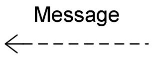
Appendix C

Sequence diagrams

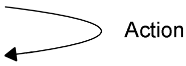
In this appendix three sequence diagrams are shown to illustrate the interactions between the different agents. A sequence diagram is a graphical representation of a certain scenario. The vertical lines (*lifelines*) show the objects that take part in the scenario and the horizontal arrows show the order in which the messages are exchanged between these objects. There are four types of arrows:

This arrow type indicates a message being send from one agent to another (no reply expected)

This arrow type indicates a message being send from one agent to another (expects a reply)



This arrow type indicates a reply being send back



This arrow type indicates an action being performed by the agent

The agents that are part of the different scenarios run in parallel, which means multiple processes can take place at the same time. This is important because in the real world there are also many processes which run in parallel. If the agents would not run parallel but instead run sequentially, the agents would not be able to work independently because they would have to wait for processes of the other agents to finish first before they can run their own processes.

The agents in the sequence diagrams are divided into two groups: simulation agents and MAS agents. The first are the agents that are needed for the experiments. These agents provide the input for the MAS agents. The latter are the agents that cooperatively control the temperature and lighting in the room.

The first sequence diagram shows a simple example of a situation where a person walks into the room and later on leaves the room. At entrance of the room the temperature is too low and the lights are off. This diagram shows how the heating agent and lighting agent react on these events.

The second sequence diagram shows a situation where a person walks into the room and where later on the sunlight becomes too bright and creates glare for the person in the room. At entrance of the room the temperature is too low, the lights are off and the blinds are up. By the time the sunlight becomes too bright the lighting agent reacts by closing the blinds.

The third sequence diagram shows a situation where a person walks into the room and where later on the illuminance outside increases and as a result it becomes desirable to raise the blinds in order to utilize the light of the sun. At entrance of the room the temperature is too high, the lights are off and the blinds are down. By the time the outdoor illuminance increases the lighting agent sends a request to the room agent to raise the blinds, but since the cooling is already on it is more sensible to just leave the lights on and not raise the blinds.

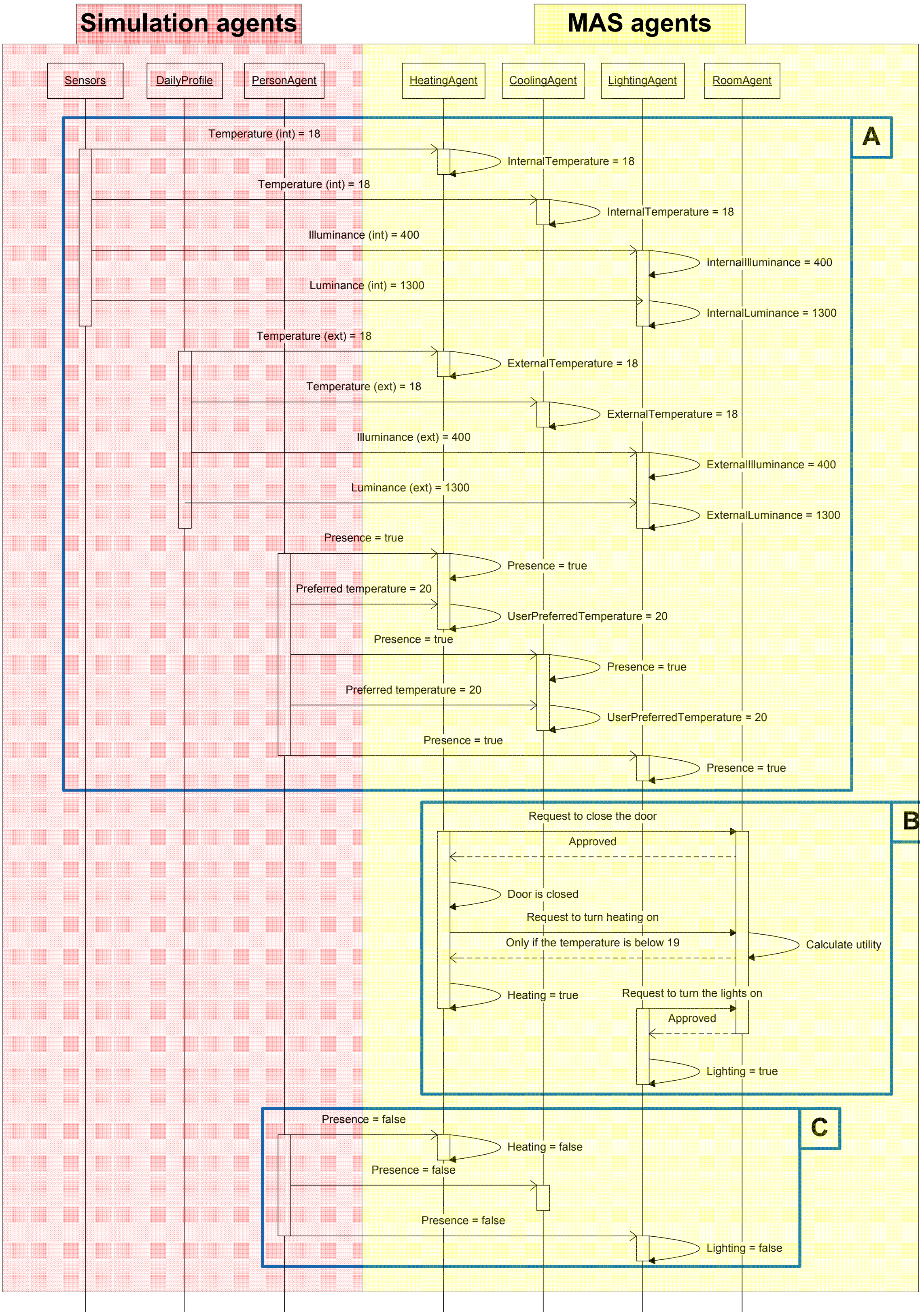


Figure C-1: Sequence diagram of heating and lighting operations. This diagram shows how the Heating Agent and the Lighting Agent react on the entrance and departure of a person. In frame A the sensors, the (simulated) scenario and the Person Agent send information to the Heating, Cooling and Lighting Agent. In frame B the Heating Agent first closes the door and then turns the heating on and the Lighting Agent turns the lights on. These actions follow after sending a request to the Room Agent which in its turn gives its approval. In frame C the person leaves the room and the Heating Agent turns off the heating while the Lighting Agent switches off the lights.

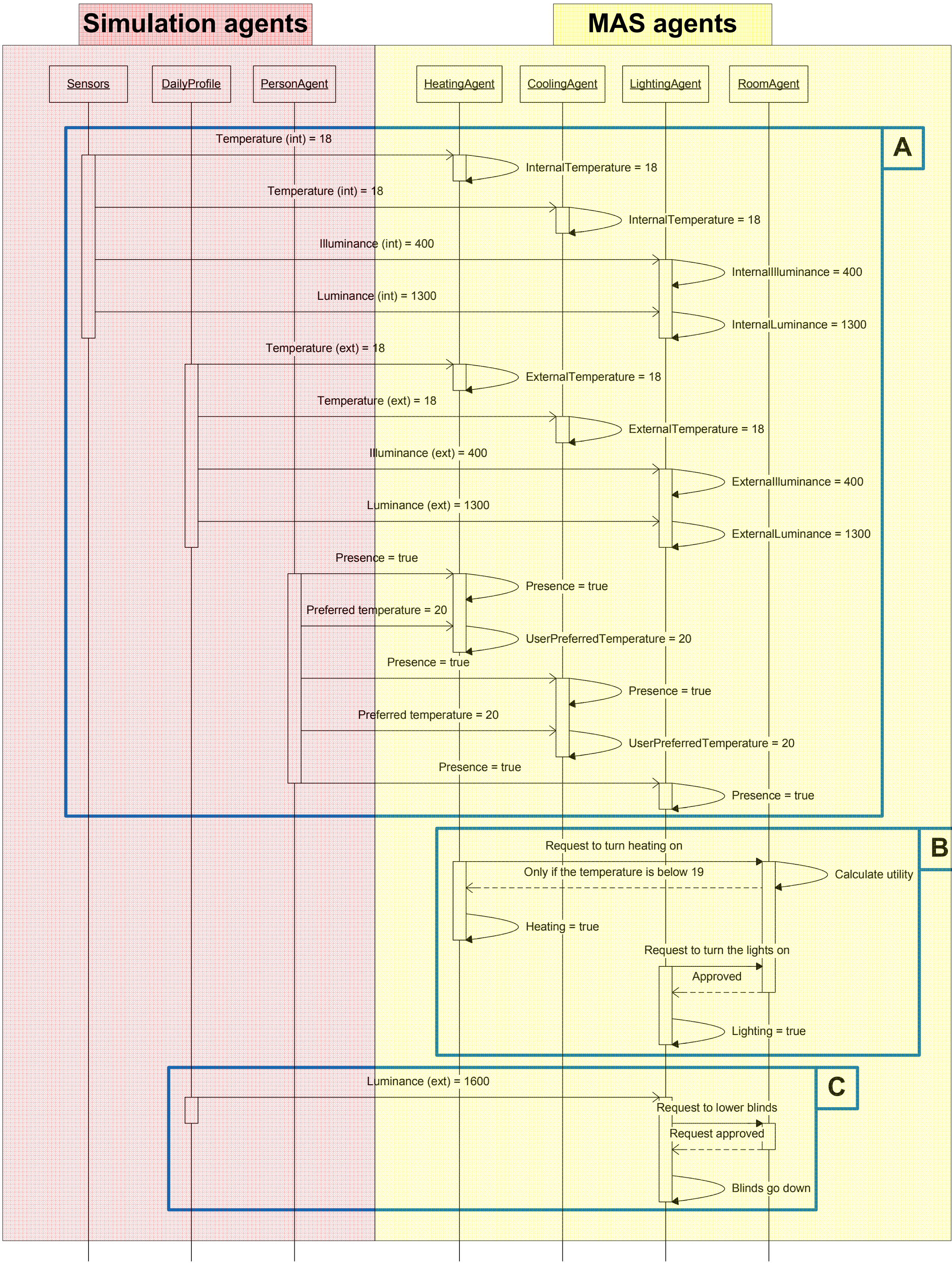


Figure C-2: Sequence diagram of heating and (lowering) blinds operations. This diagram shows how the Heating Agent and Lighting Agent react on the entrance of a person and how the lighting agent reacts on a situation with glare. In frame A the sensors, the (simulated) scenario and the Person Agent send information to the Heating, Cooling and Lighting Agent. In frame B the Heating Agent turns the heating on and the Lighting Agent turns the lights on (both after receiving approval from the Room Agent). In frame C the external luminance raises above 1500 cd/m2 (which means there is glare) and the Lighting Agent lowers the blinds (again after receiving an approval from the Room Agent).

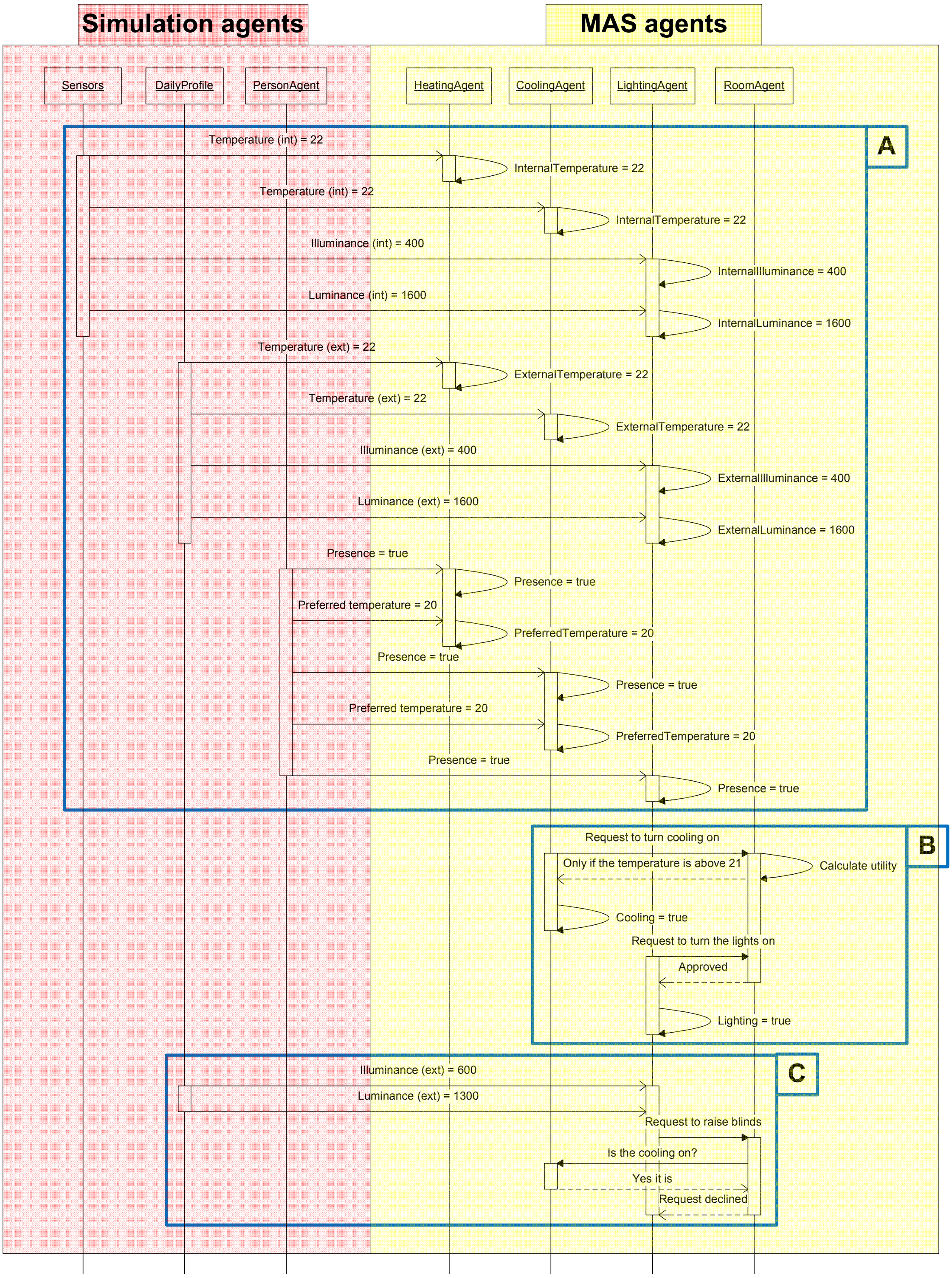


Figure C-3: Sequence diagram of cooling and (raising) blinds operations. This diagram shows how the Cooling Agent and Lighting Agent react on the entrance of a person and how the lighting agent reacts on a situation where natural lighting can be utilized. In frame A the sensors, the (simulated) scenario and the Person Agent send information to the Heating, Cooling and Lighting Agent. In frame B the Cooling Agent turns the cooling on and the Lighting Agent turns the lights on (both after receiving approval from the Room Agent). In frame C the external illuminance raises above 600 lux (which means sunlight can be used to lighten the room) and the Lighting Agent sends a request to raise the blinds, but since the cooling is on it means that the temperature in the room is already high so this time the Room Agent declines the request in order to save energy.

Appendix D

Class diagrams

In this appendix three class diagrams are shown. A class diagram describes the structure of a system by showing the system's classes and the relationships among the classes. The classes consist of three parts:

- The upper part contains the name of the class.
- The middle part contains the attributes of the class.
- The bottom part contains the methods of the class.

The attributes and methods of the classes in this appendix are either Public (+) or Private (-). Public means that the attribute or method is visible for all other classes and private means that these are not visible for other classes.

The first class diagram shows the relationships between the four MAS agents. Also the attributes and methods of each individual agent are shown.

The second class diagram shows the generalization relationships between subclasses and superclasses. A subclass is considered to be a specialized form of the superclass. This means that any instance of the subclass is also an instance of the superclass.

The other class diagrams show the dependency relationships between classes. This type of relationships shows that one class depends on one or more other classes because it uses these at some point of time.

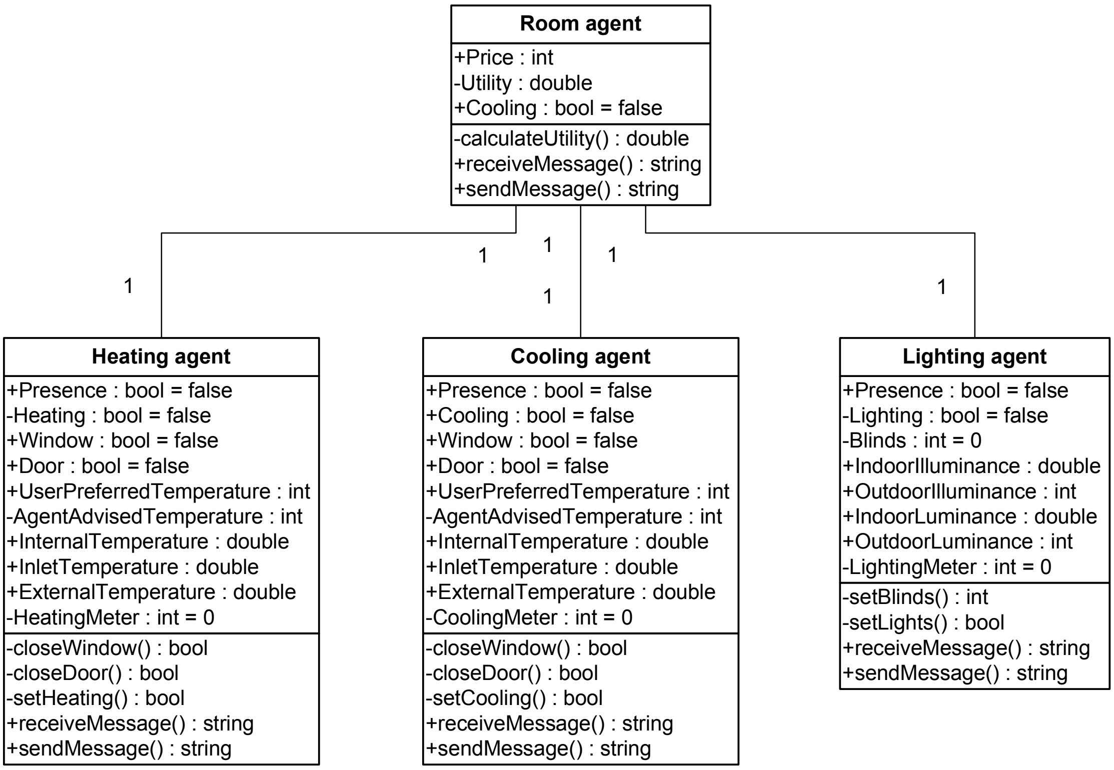


Figure D-1: Instance level relationship. All agents have a bi-directional association with the room agent, which means that messages can be send both ways. Also the room agent can only have one heating agent, one cooling agent and one lighting agent and vice versa.

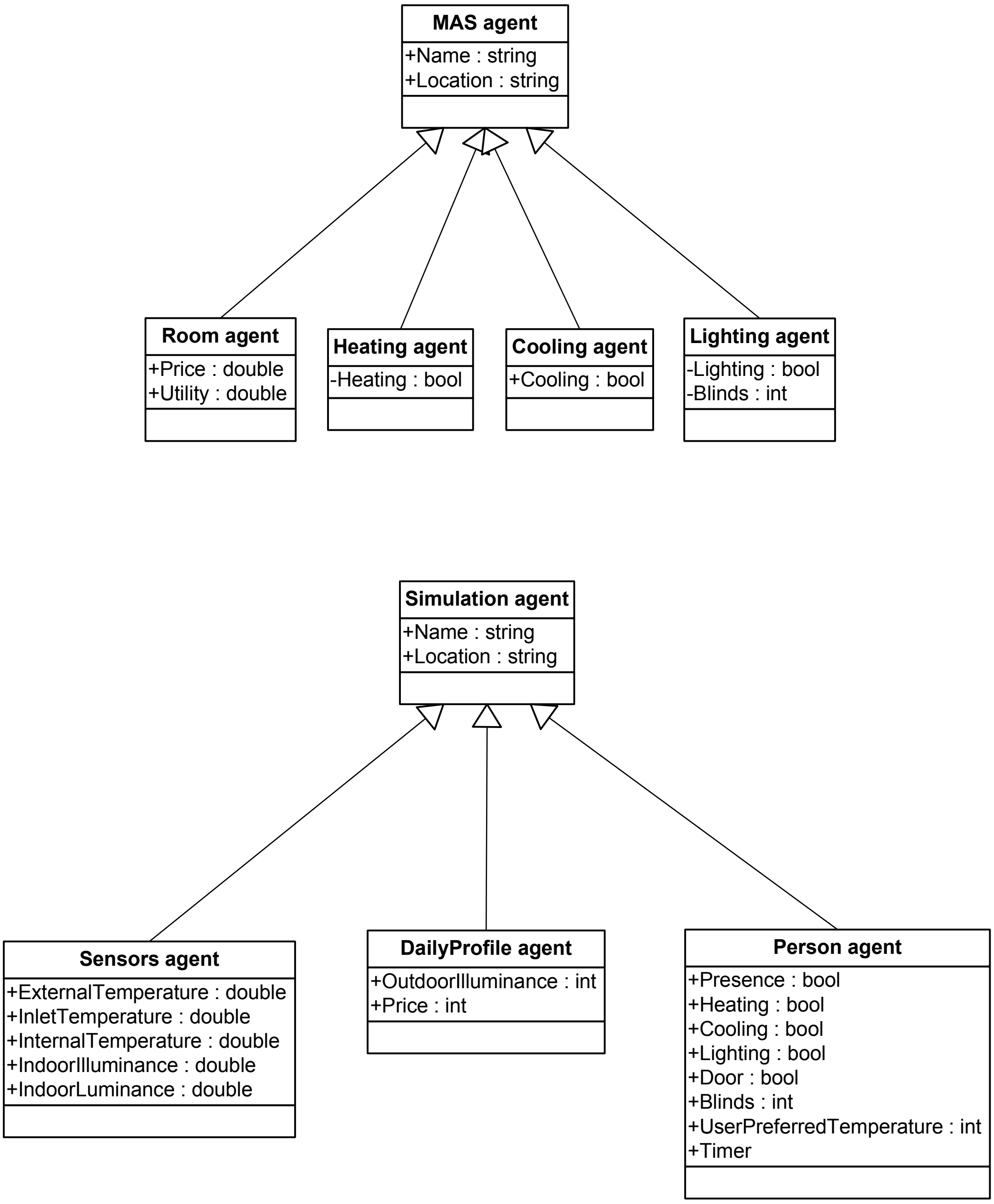


Figure D-2: Generalization relationships. The room agent, heating agent, cooling agent and lighting agent are all four subclasses of the superclass MAS agent. And the sensors agent, DailyProfile agent and person agent are all three subclasses of the superclass Simulation agent.

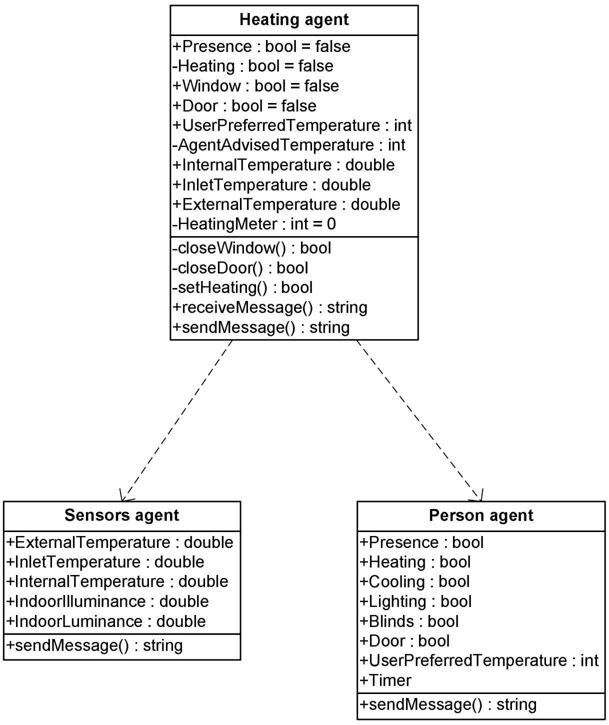


Figure D-3: Dependency relationship heating agent. The heating agent makes use of the sensors agent and the person agent. The attributes of all agents are of a certain type (boolean, integer, double or string), except for the Timer attribute of the person agent which is of a special type. Some attributes of the heating agent, i.e. Presence, Heating, Window and Door, have initial values.

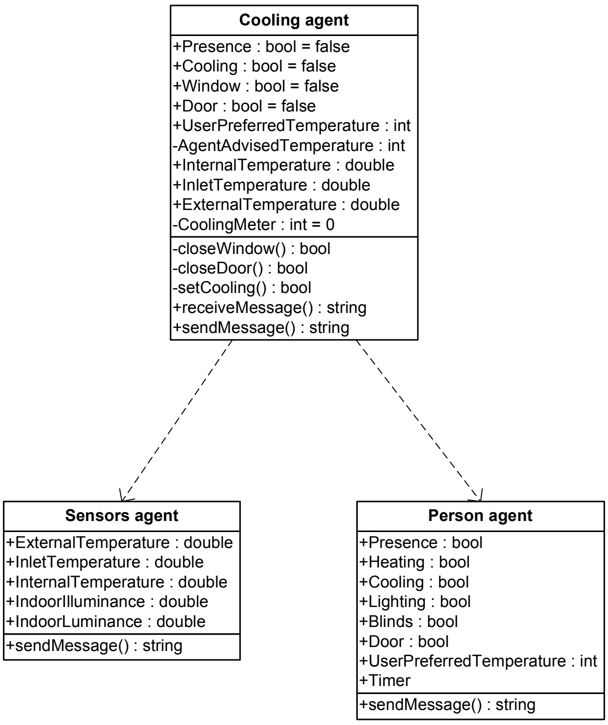


Figure D-4: Dependency relationship cooling agent. The cooling agent makes use of the sensors agent and the person agent. The attributes of all agents are of a certain type (boolean, integer, double or string), except for the Timer attribute of the person agent which is of a special type. Some attributes of the cooling agent, i.e. Presence, Heating, Window and Door, have initial values.

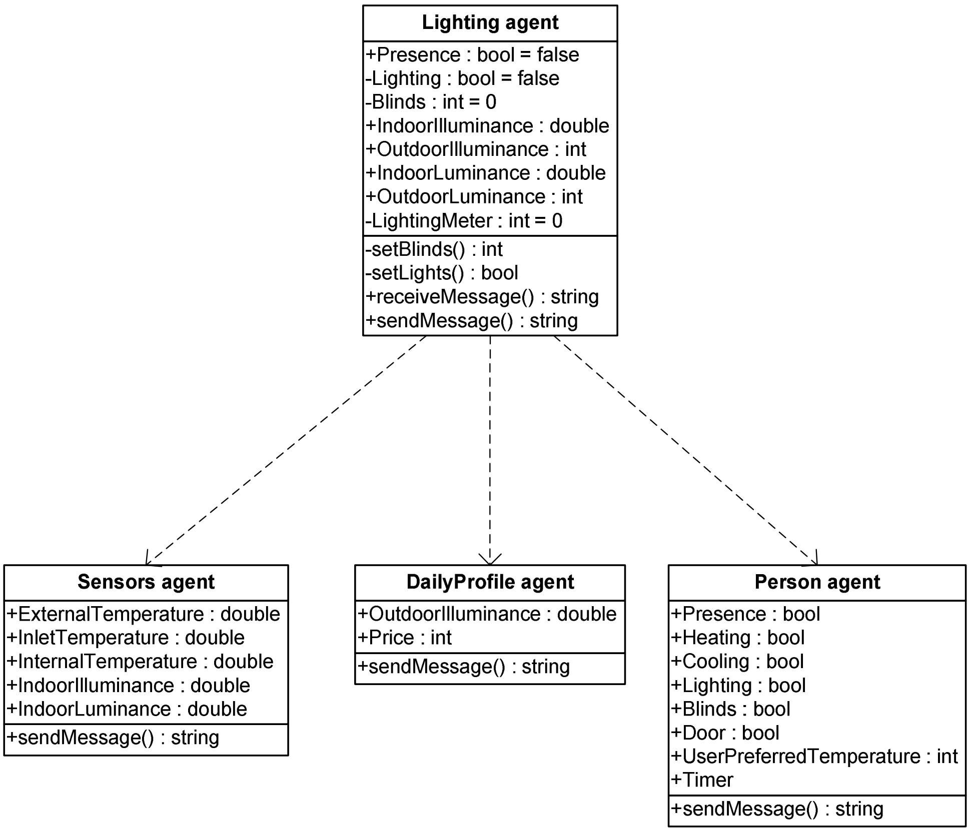


Figure D-5: Dependency relationship lighting agent. The lighting agent makes use of the sensors agent, the DailyProfile agent and the person agent. The attributes of all agents are of a certain type (boolean, integer, double or string), except for the Timer attribute of the person agent which is of a special type. Some attributes of the lighting agent, i.e. Presence and Lighting, have initial values.

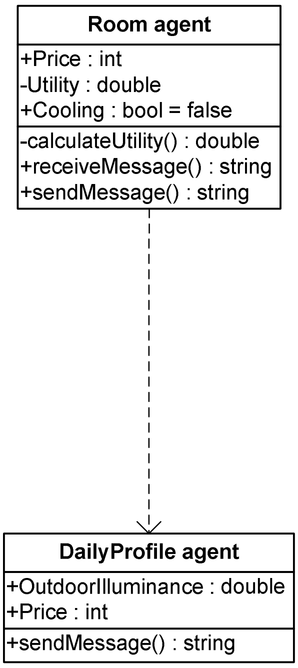


Figure D-6: Dependency relationship room agent. The room agent makes use of the DailyProfile agent. The attributes of both agents are of a certain type (boolean, integer, double or string). One attributes of the room agent, i.e. Cooling, has an initial values.

Appendix E

Measurement results

In this appendix all 16 scenarios are shown. The graphs show the measurements of the five sensors. On top of each page there is a small description of the scenario. The scenarios are numbered from 1.1 to 1.4.

Each page contains two figures. Basically these figures show the same measurement data, but the bottom figure also shows the energy loads, i.e. lighting, heating or cooling loads.

Each figure contains two graphs: a lighting graph and a temperature graph. The top graph shows the lighting measurements, i.e. the indoor illuminance and the indoor luminance. The bottom graph shows the temperature measurements, i.e. the external temperature, inlet temperature and internal temperature. The white boxes with a red edge below the graphs show the operations on specific times.

Since the external temperature of the room, which equals the temperature inside the laboratory, cannot be controlled by the MAS and is always around 24 ^{o}C, a summer day is represented by setting the user's preferred temperature to 26 or 27 ^{o}C and a winter day is represented by setting the user's preferred temperature to 21 or 22 ^{o}C.

Scenario 1.1

User: energy waster, preferred temperature 27 °C

Control: manual control, static blinds, static price

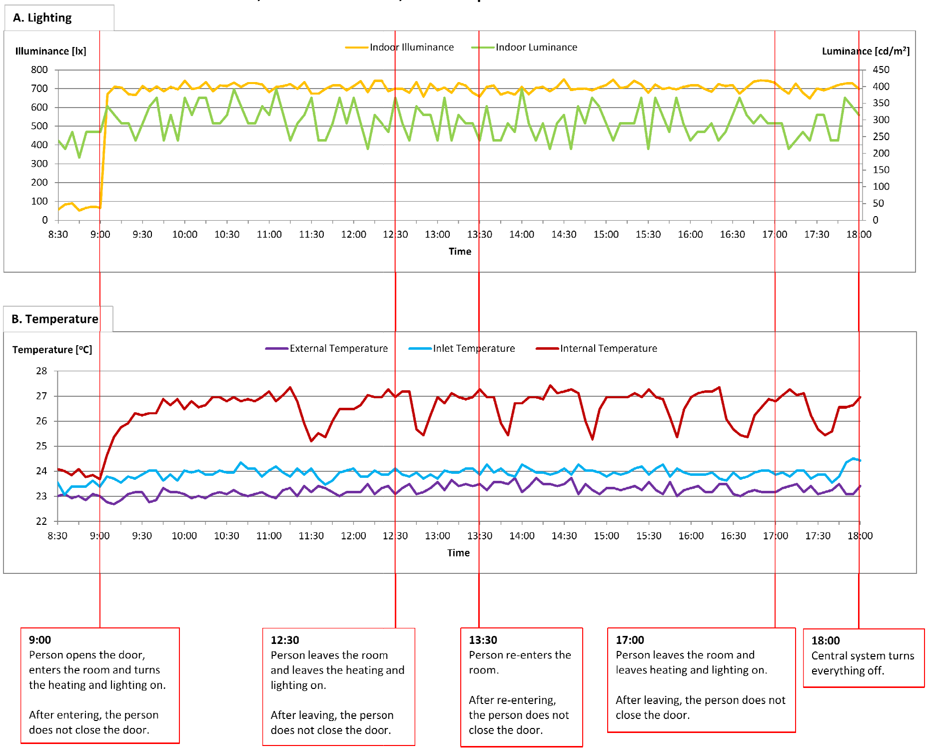


Figure E-1: Results of energy waster with manual control. This scenario represents a regular working day in winter. The person working in the room is someone who does not care about energy loads. The blinds are static and are always fully down. The person enters the room at 9:00, turns the lights on and sets the thermostat to 27 °C. He never turns the lighting or heating off, even not when he leaves for home at 17:00. The central system automatically turns the heating and lighting off at 18:00.

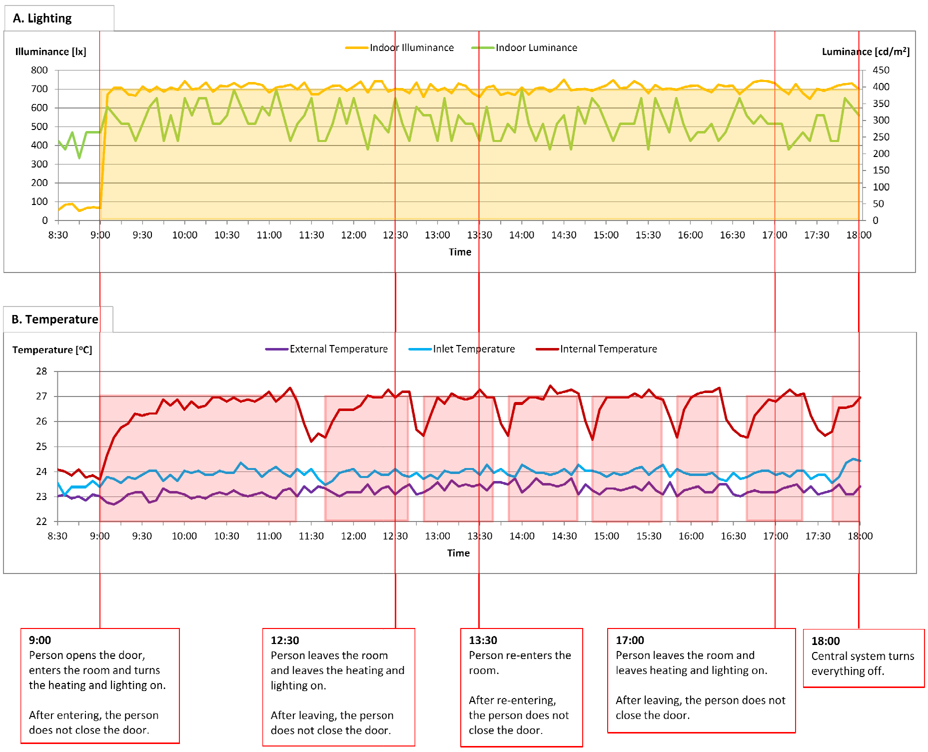


Figure E-1a: The same as figure E-1, except this time the lighting and heating loads are included in the graphs.

Scenario 1.2

User: energy waster, preferred temperature 27 °C

Control: MAS control, static blinds, static price

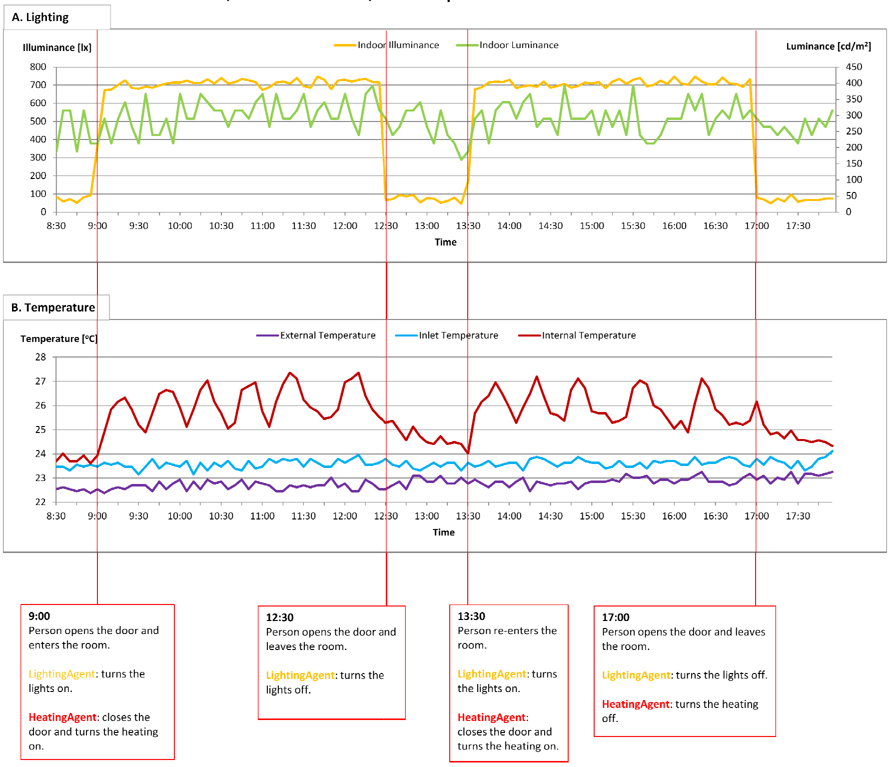


Figure E-2: Results of energy waster with MAS control. This scenario represents a regular working day in winter. The person working in the room is someone who does not care about energy loads. The blinds are static and are always fully down. The person enters the room at 9:00, sets the thermostat to 27 °C and leaves for home at 17:00. Between these hours he never turns the heating or lighting on or off, but fully relies on the MAS for control of both these systems.

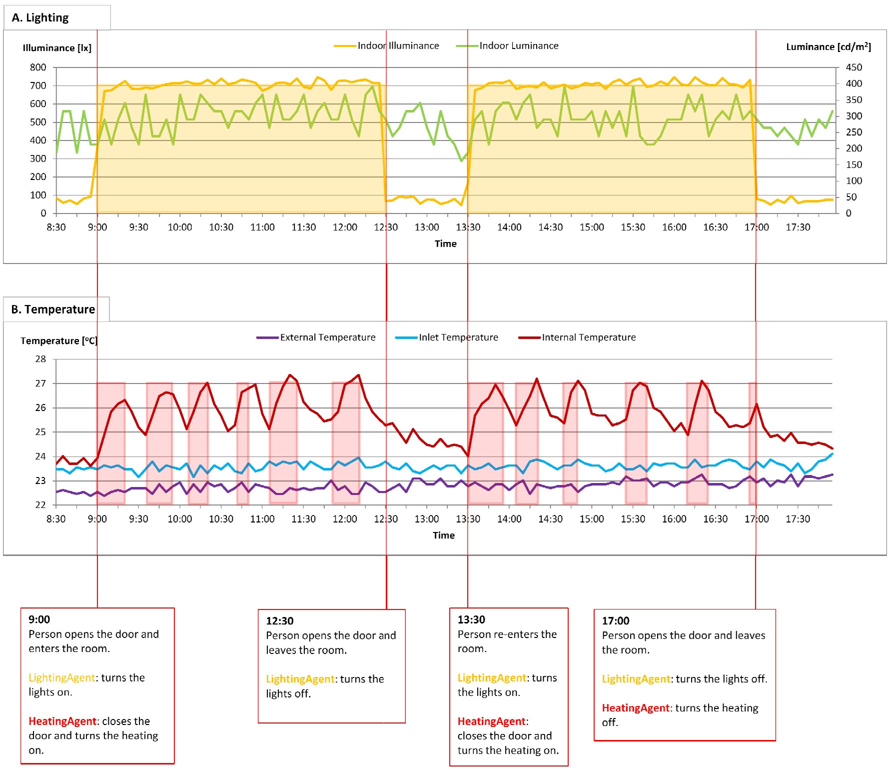


Figure E-2a: The same as figure E-2, except this time the lighting and heating loads are included in the graphs.

Scenario 1.3

User: energy waster, preferred temperature 27 °C

Control: MAS control, dynamic blinds, static price

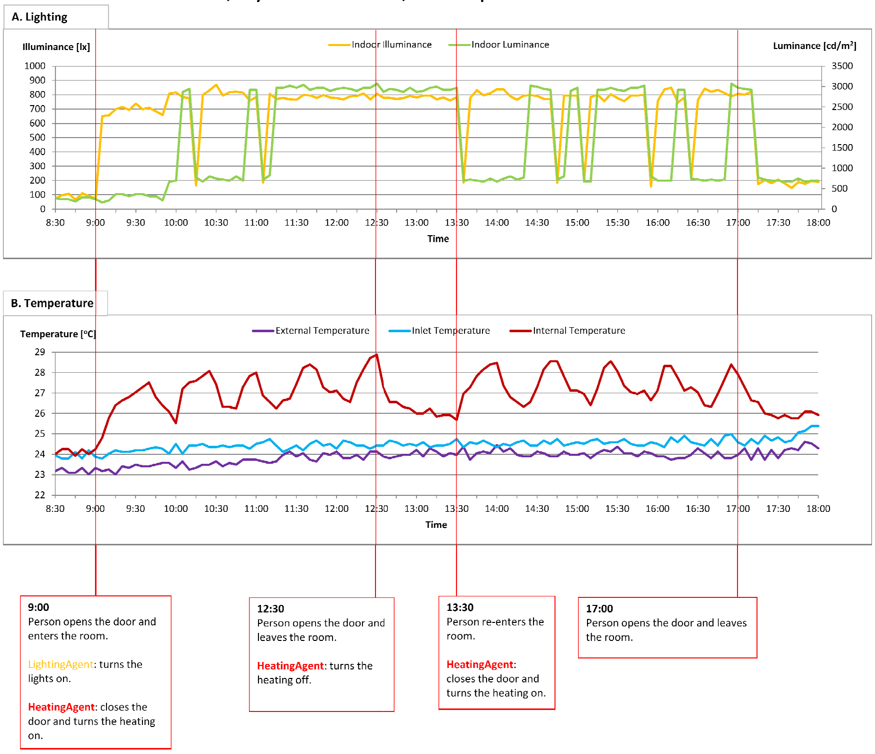


Figure E-3: : Results of energy waster with MAS control and dynamic blinds. This scenario represents a regular working day in winter. The person working in the room is someone who does not care about energy loads. The person enters the room at 9:00, sets the thermostat to 27 °C and leaves for home at 17:00. Between these hours he never turns the heating or lighting on or off and never raises or lowers the blinds, but fully relies on the MAS for control of all these three systems.

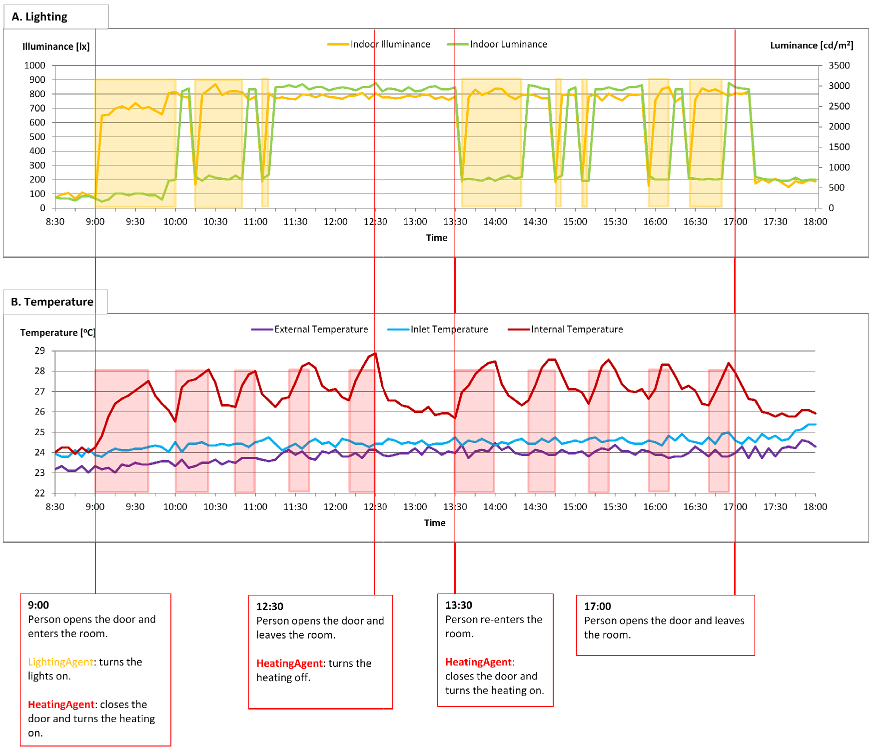


Figure E-3a: The same as figure E-3, except this time the lighting and heating loads are included in the graphs.

Scenario 1.4

User: energy waster, preferred temperature 27 °C

Control: MAS control, dynamic blinds, dynamic price

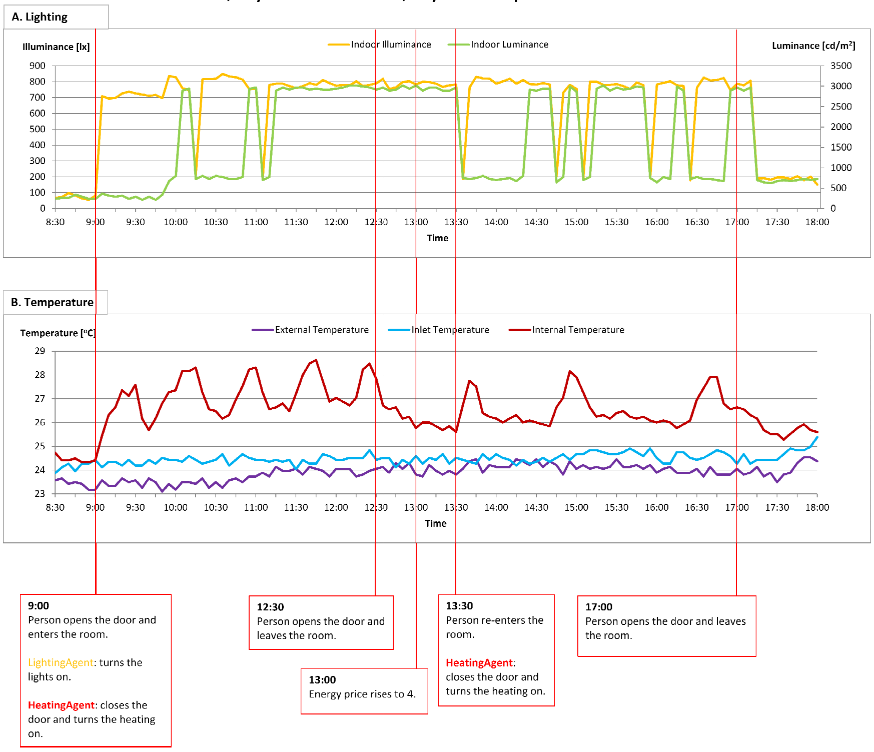


Figure E-4: Results of energy waster with MAS control, dynamic blinds and a fluctuating energy price. This scenario represents a regular working day in winter. The person working in the room is someone who does not care about energy loads. The person enters the room at 9:00, sets the thermostat to 27 °C and leaves for home at 17:00. Between these hours he never turns the heating or lighting on or off and never raises or lowers the blinds, but fully relies on the MAS for control of all these three systems. In the morning the energy price is 2 and in the afternoon the energy price is 4.

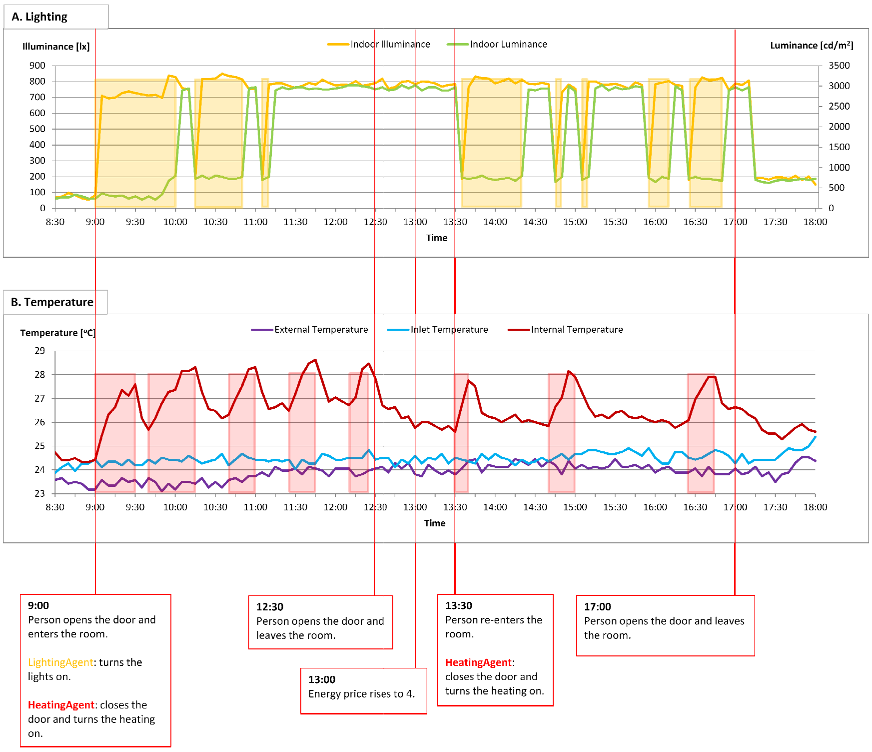


Figure E-4a: The same as figure E-4, except this time the lighting and heating loads are included in the graphs.

Scenario 2.1

User: energy waster, preferred temperature 21 °C

Control: manual control, static blinds, static price

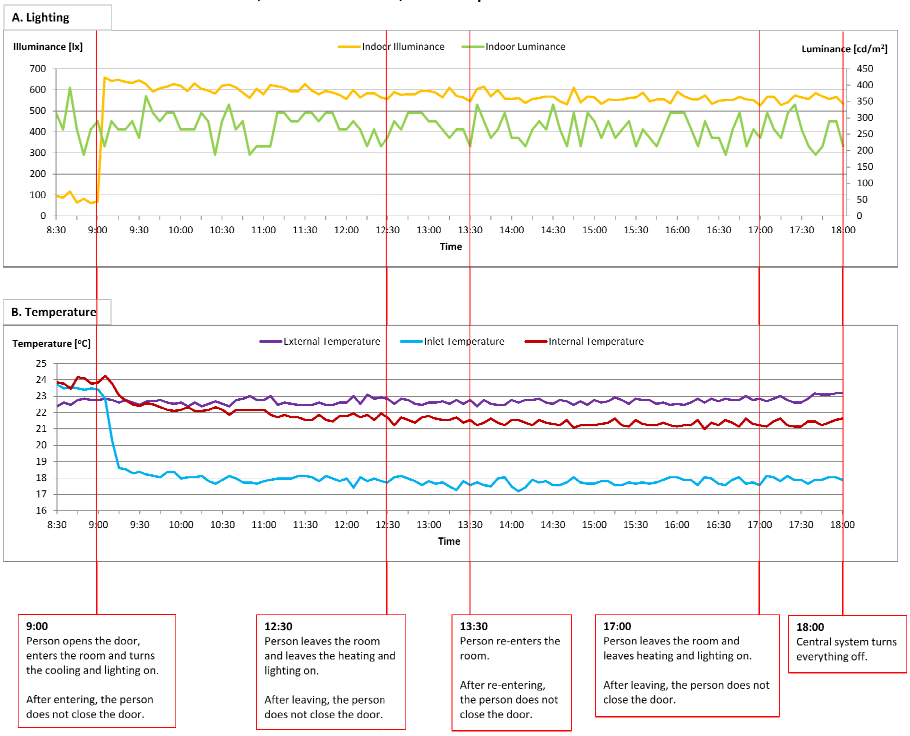


Figure E-5: Results of energy waster with manual control. This scenario represents a regular working day in summer. The person working in the room is someone who does not care about energy loads. The blinds are static and are always fully down. The person enters the room at 9:00, turns the lights on and sets the thermostat to 21 °C. He never turns the lighting or cooling off, even not when he leaves for home at 17:00. The central system automatically turns the cooling and lighting off at 18:00.

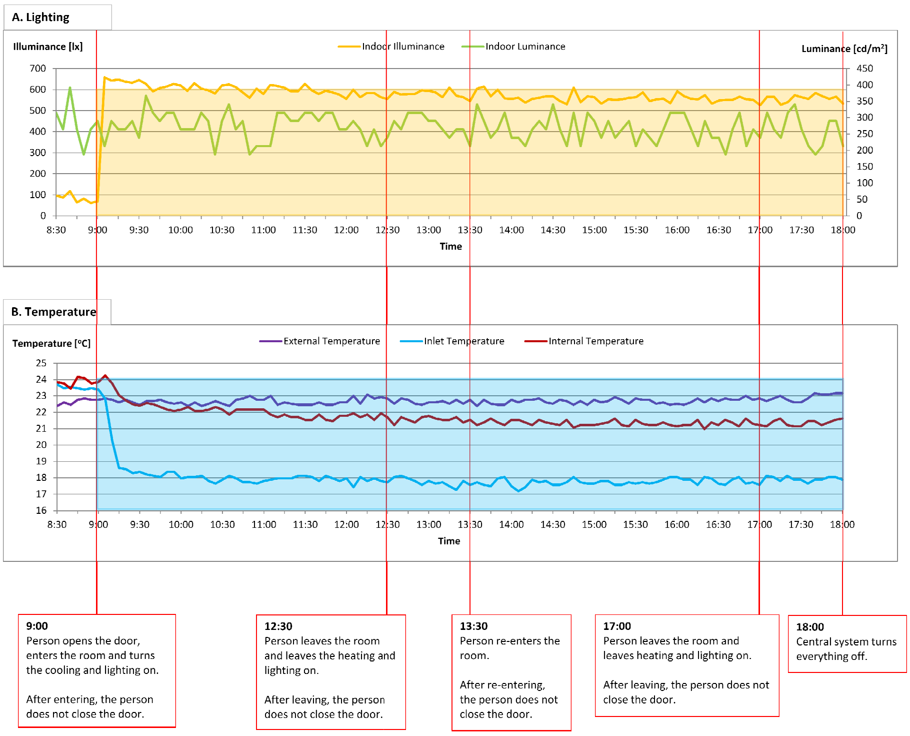


Figure E-5a: The same as figure E-5, except this time the lighting and cooling loads are included in the graphs.

Scenario 2.2

User: energy waster, preferred temperature 21 °C

Control: MAS control, static blinds, static price

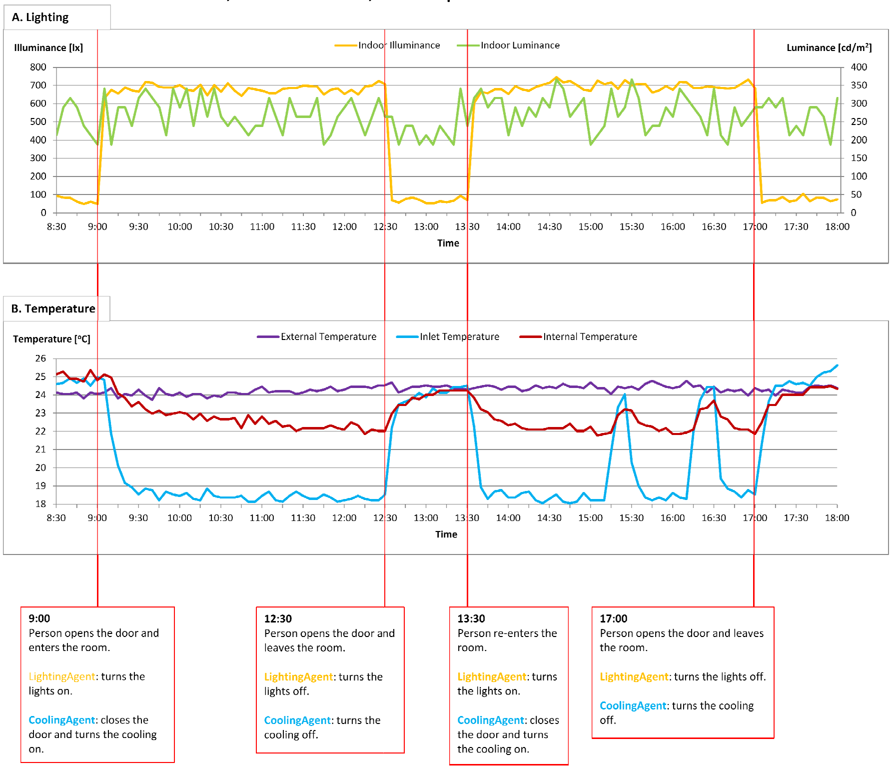


Figure E-6: Results of energy waster with MAS control. This scenario represents a regular working day in summer. The person working in the room is someone who does not care about energy loads. The blinds are static and are always fully down. The person enters the room at 9:00, sets the thermostat to 21 °C and leaves for home at 17:00. Between these hours he never turns the cooling or lighting on or off, but fully relies on the MAS for control of both these systems.

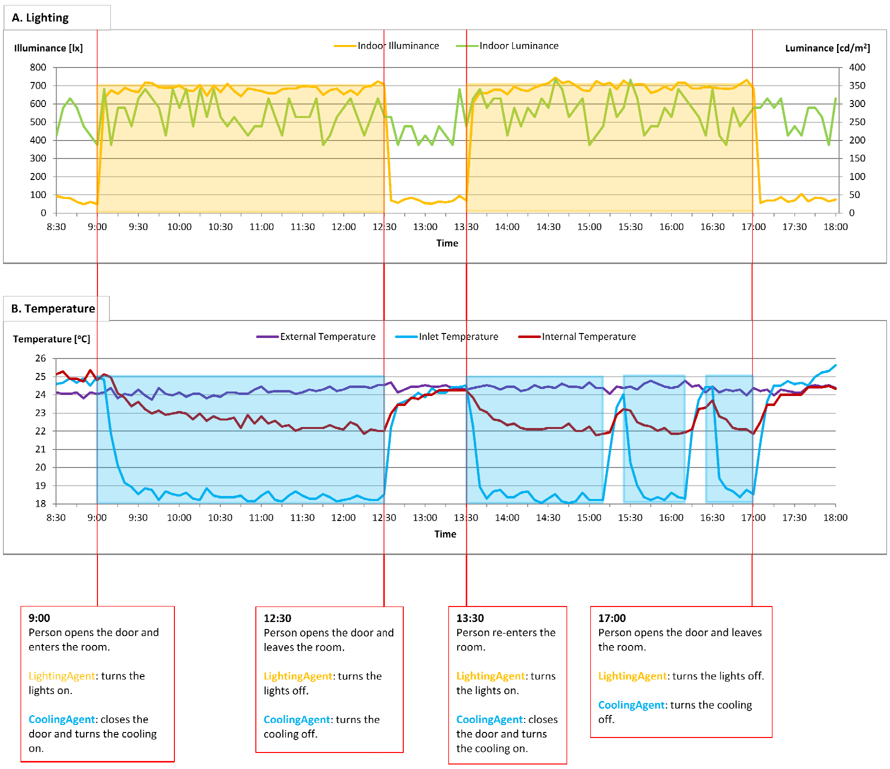


Figure E-6a: The same as figure E-6, except this time the lighting and cooling loads are included in the graphs.

Scenario 2.3

User: energy waster, preferred temperature 21 °C

Control: MAS control, dynamic blinds, static price

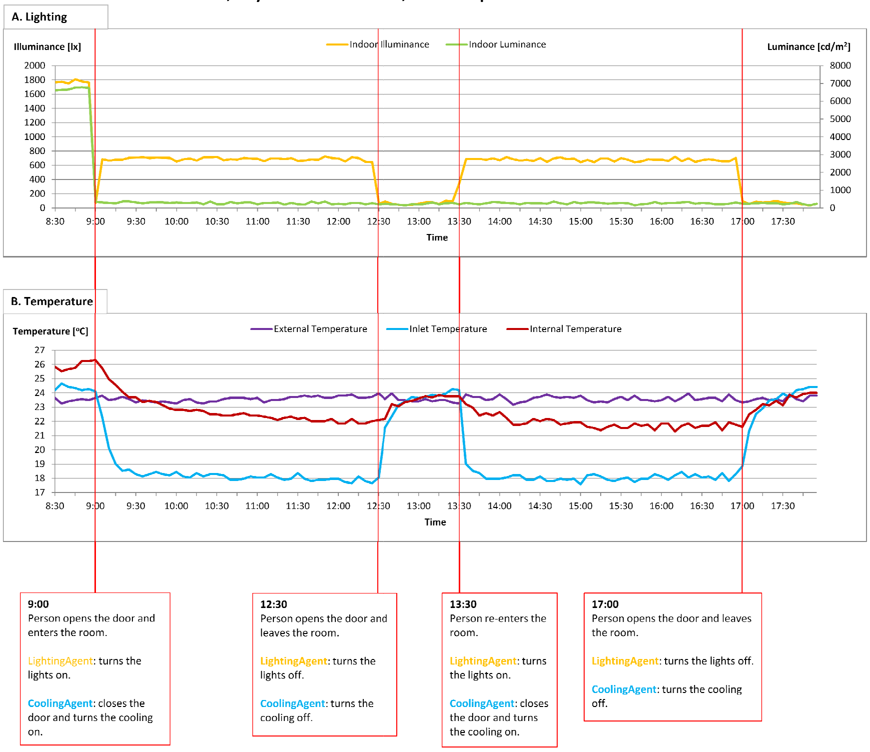


Figure E-7: Results of energy waster with MAS control and dynamic blinds. This scenario represents a regular working day in summer. The person working in the room is someone who does not care about energy loads. The person enters the room at 9:00, sets the thermostat to 21 °C and leaves for home at 17:00. Between these hours he never turns the cooling or lighting on or off and never raises or lowers the blinds, but fully relies on the MAS for control of all these three systems.

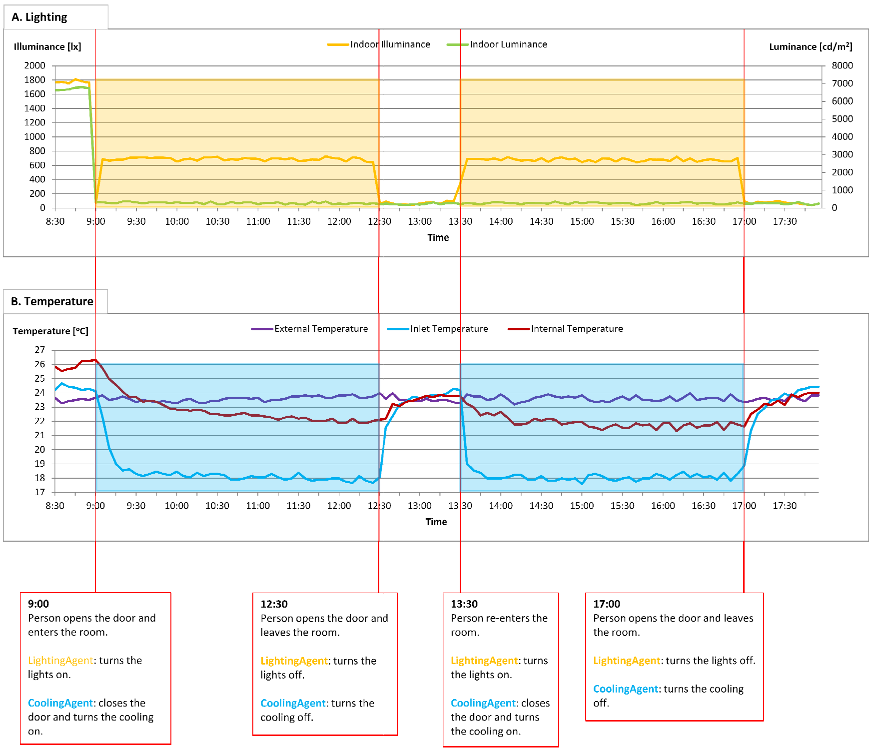


Figure E-7a: The same as figure E-7, except this time the lighting and cooling loads are included in the graphs.

Scenario 2.4

User: energy waster, preferred temperature 21 ^{o}C

Control: MAS control, dynamic blinds, dynamic price

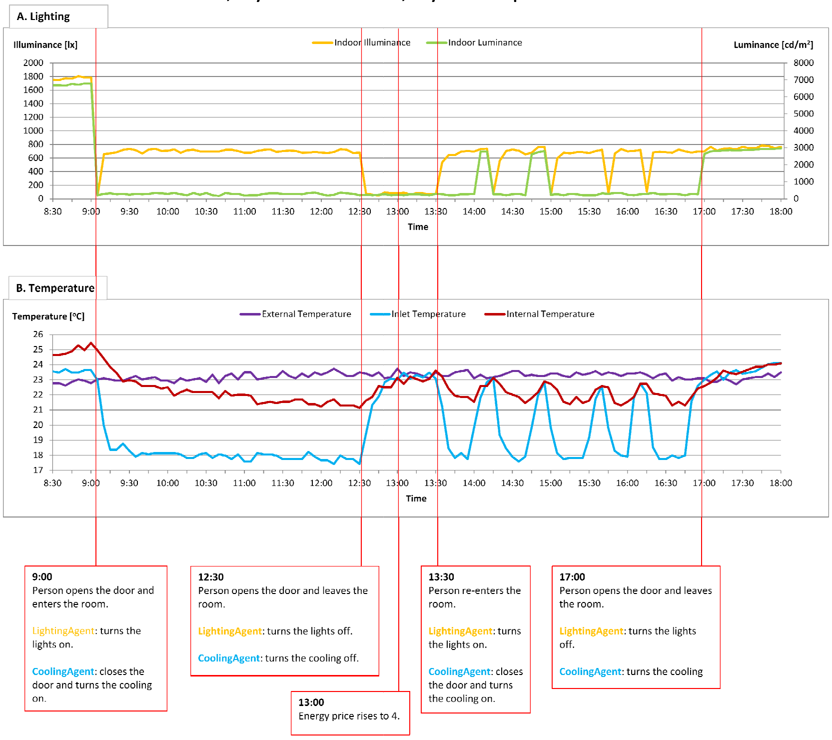


Figure E-8: Results of energy waster with MAS control, dynamic blinds and a fluctuating energy price. This scenario represents a regular working day in summer. The person working in the room is someone who does not care about energy loads. The person enters the room at 9:00, sets the thermostat to 21 ^{o}C and leaves for home at 17:00. Between these hours he never turns the cooling or lighting on or off and never raises or lowers the blinds, but fully relies on the MAS for control of all these three systems. In the morning the energy price is 2 and in the afternoon the energy price is 4.

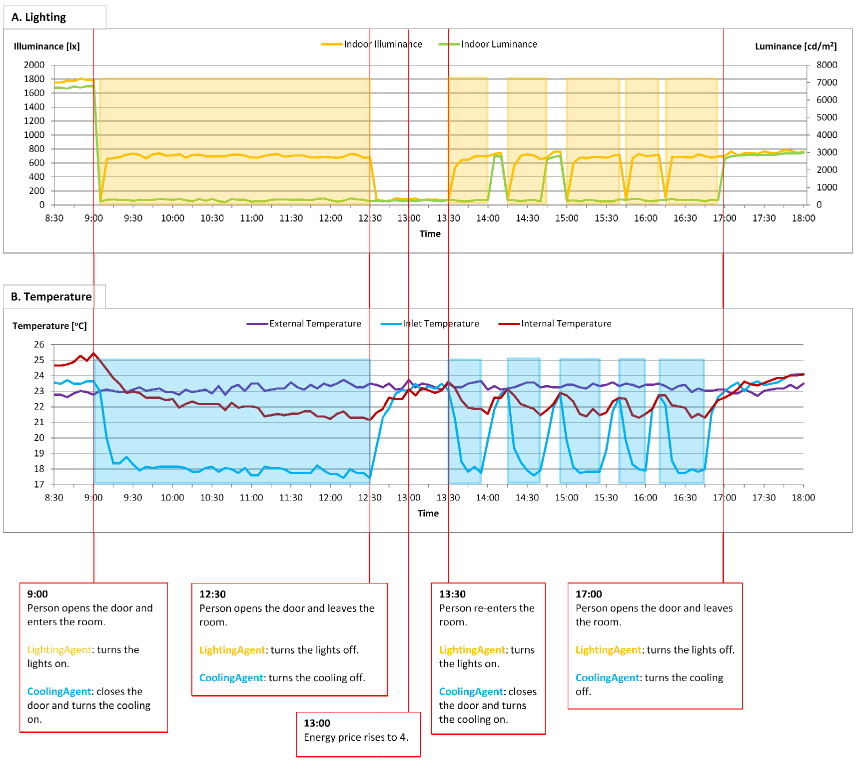


Figure E-8a: The same as figure E-8, except this time the lighting and cooling loads are included in the graphs.

Scenario 3.1

User: energy saver, preferred temperature 26 °C

Control: manual control, static blinds, static price

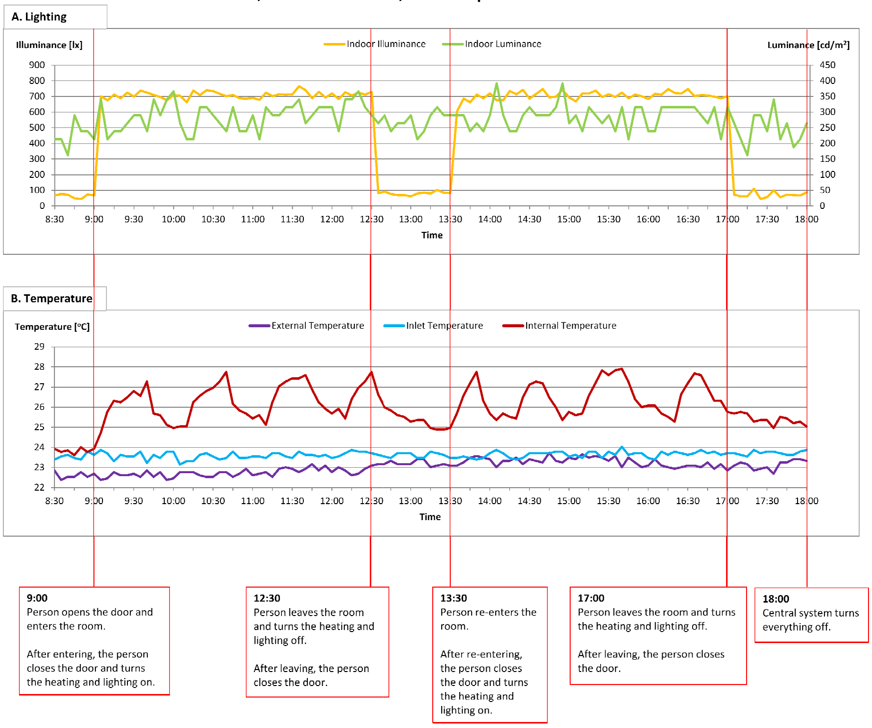


Figure E-9: Results of energy saver with manual control. This scenario represents a regular working day in winter. The person working in the room is someone who tries to save energy whenever possible. The blinds are static and are always fully down. The person enters the room at 9:00, turns the heating and lighting on, sets the thermostat to 26 °C and closes the door when he is inside. He also always turns the heating and lighting off when he leaves the room. The central system automatically turns the heating and lighting off at 18:00, but in this case it is unnecessary because the person already turned everything off when he left for home.

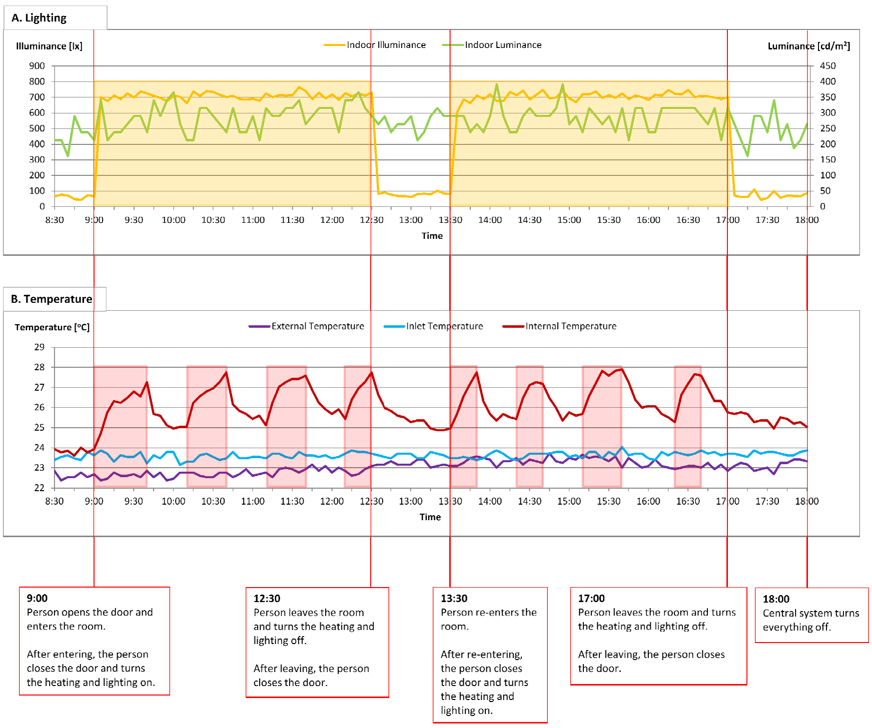


Figure E-9a: The same as figure E-9, except this time the lighting and heating loads are included in the graphs.

Scenario 3.2

User: energy saver, preferred temperature 26 °C

Control: MAS control, static blinds, static price

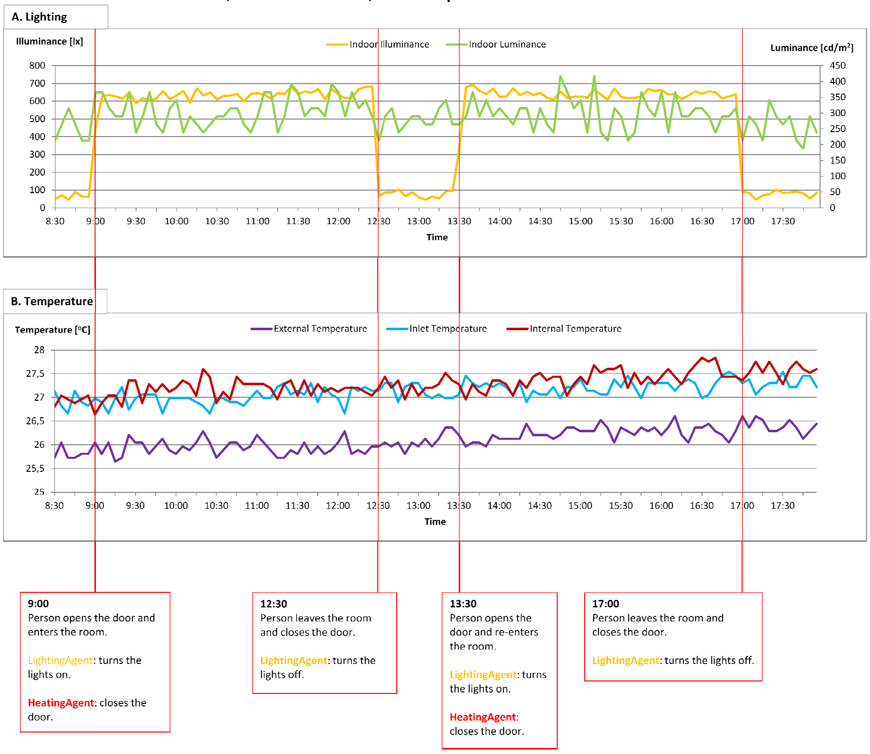


Figure E-10: Results of energy saver with MAS control. This scenario represents a regular working day in winter. The person working in the room is someone who tries to save energy whenever possible. The blinds are static and are always fully down. The person enters the room at 9:00, sets the thermostat to 26 °C and leaves for home at 17:00. Between these hours he never has to turn the heating or lighting on or off, because the MAS automatically takes care of it.

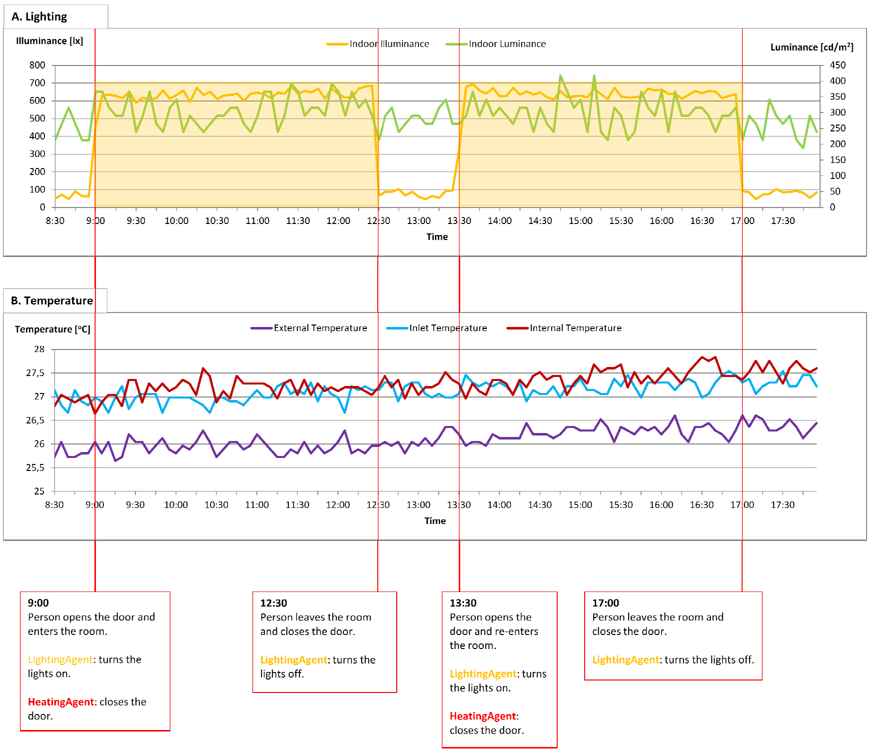


Figure E-10a: The same as figure E-10, except this time the lighting and heating loads are included in the graphs.

Scenario 3.3

User: energy saver, preferred temperature 26 °C

Control: MAS control, dynamic blinds, static price

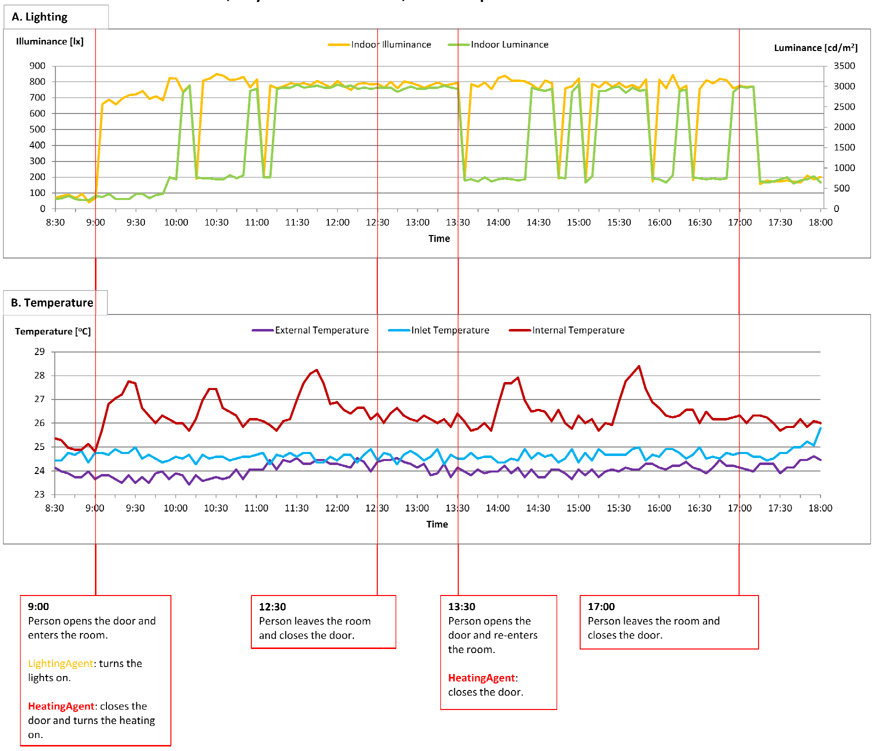


Figure E-11: Results of energy saver with MAS control and dynamic blinds. This scenario represents a regular working day in winter. The person working in the room is someone who tries to save energy whenever possible. The person enters the room at 9:00, sets the thermostat to 26 °C and leaves for home at 17:00. Between these hours he never has to turn the heating or lighting on or off and never has to raise or lower the blinds, because he can fully rely on the MAS for the control of all these three systems.

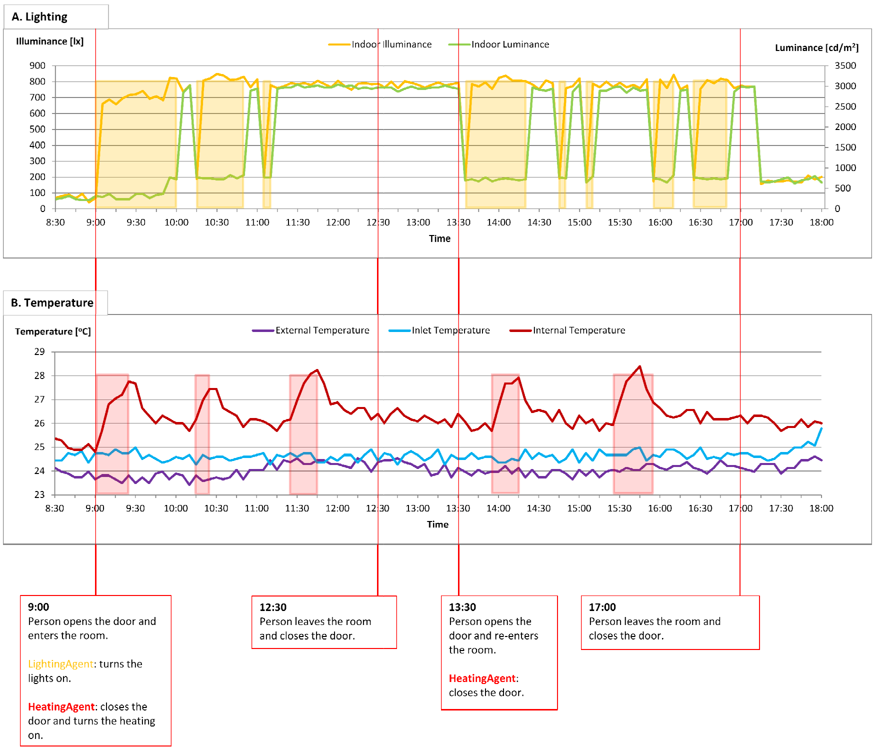


Figure E-11a: The same as figure E-11, except this time the lighting and heating loads are included in the graphs.

Scenario 3.4

User: energy saver, preferred temperature 26 °C

Control: MAS control, dynamic blinds, dynamic price

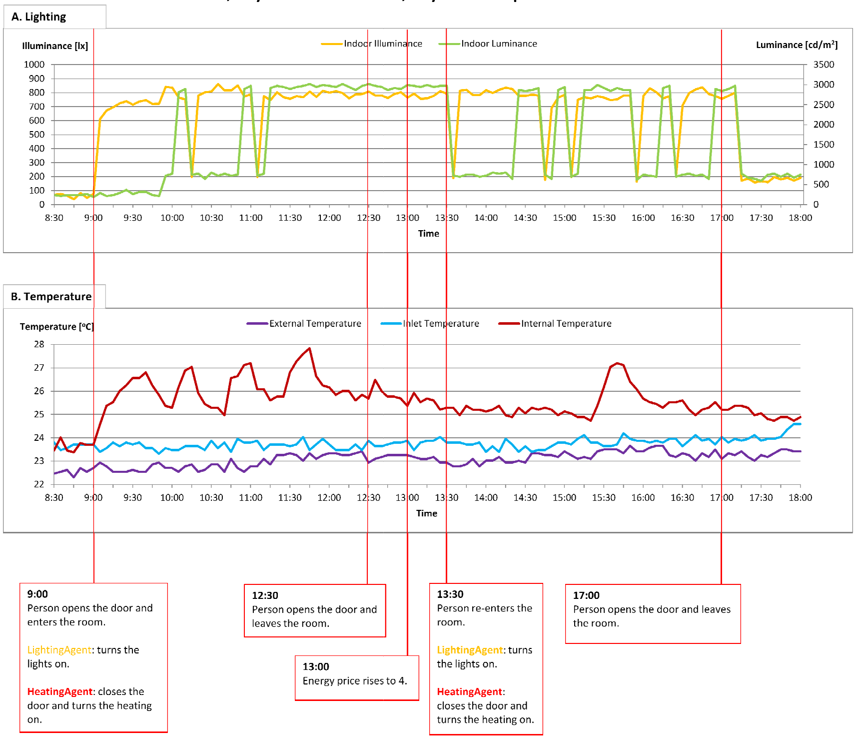


Figure E-12: Results of energy saver with MAS control, dynamic blinds and a fluctuating energy price. This scenario represents a regular working day in winter. The person working in the room is someone who tries to save energy whenever possible. The person enters the room at 9:00, sets the thermostat to 26 °C and leaves for home at 17:00. Between these hours never has to turn the heating or lighting on or off and never has to raise or lower the blinds, because he can fully rely on the MAS for control of all these three systems. In the morning the energy price is 2 and in the afternoon the energy price is 4.

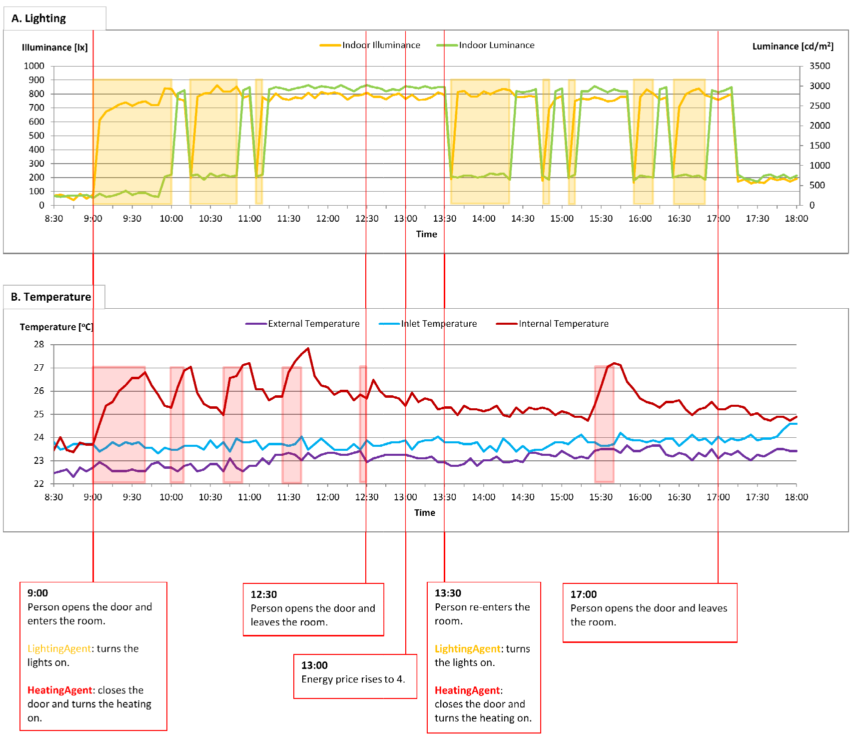


Figure E-12a: The same as figure E-12, except this time the lighting and heating loads are included in the graphs.

Scenario 4.1

User: energy saver, preferred temperature 22 °C

Control: manual control, static blinds, static price

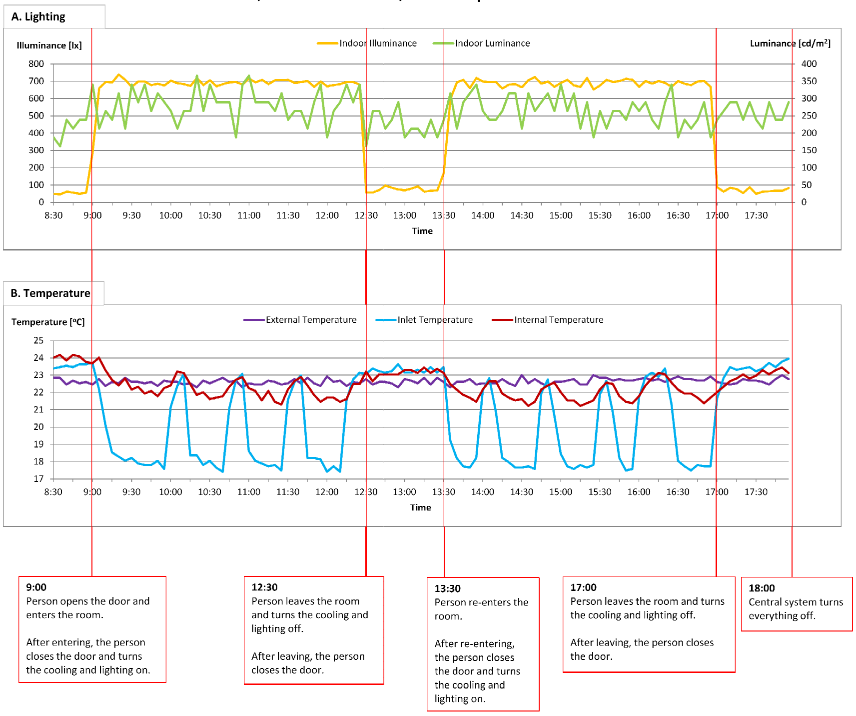


Figure E-13: Results of energy saver with manual control. This scenario represents a regular working day in summer. The person working in the room is someone who tries to save energy whenever possible. The blinds are static and are always fully down. The person enters the room at 9:00, turns the cooling and lighting on, sets the thermostat to 22 °C and closes the door when he is inside. He also always turns the cooling and lighting off when he leaves the room. The central system automatically turns the cooling and lighting off at 18:00, but in this case it is unnecessary because the person already turned everything off when he left for home.

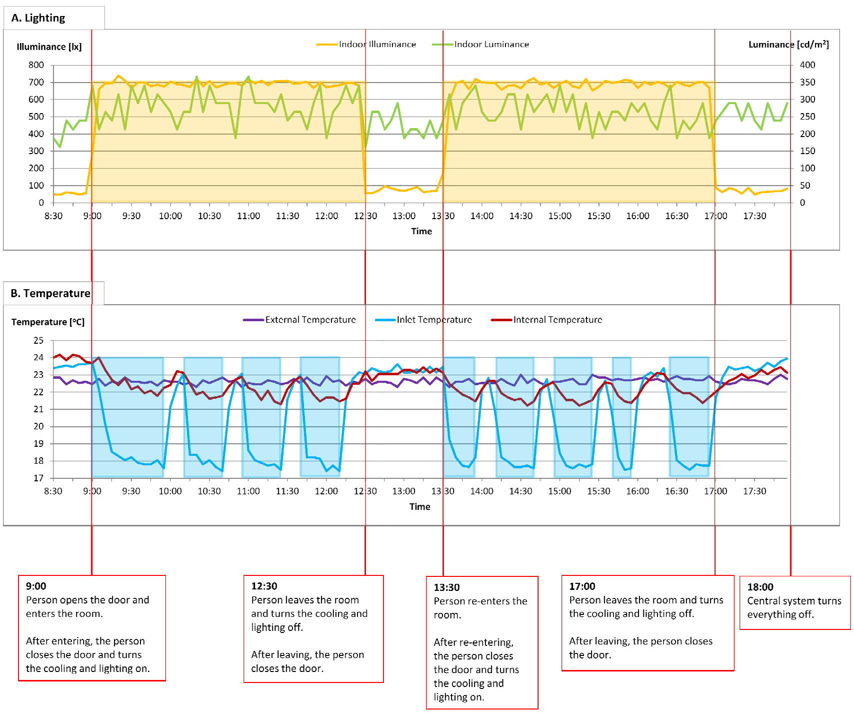


Figure E-13a: The same as figure E-13, except this time the lighting and cooling loads are included in the graphs.

Scenario 4.2

User: energy saver, preferred temperature 22 °C

Control: MAS control, static blinds, static price

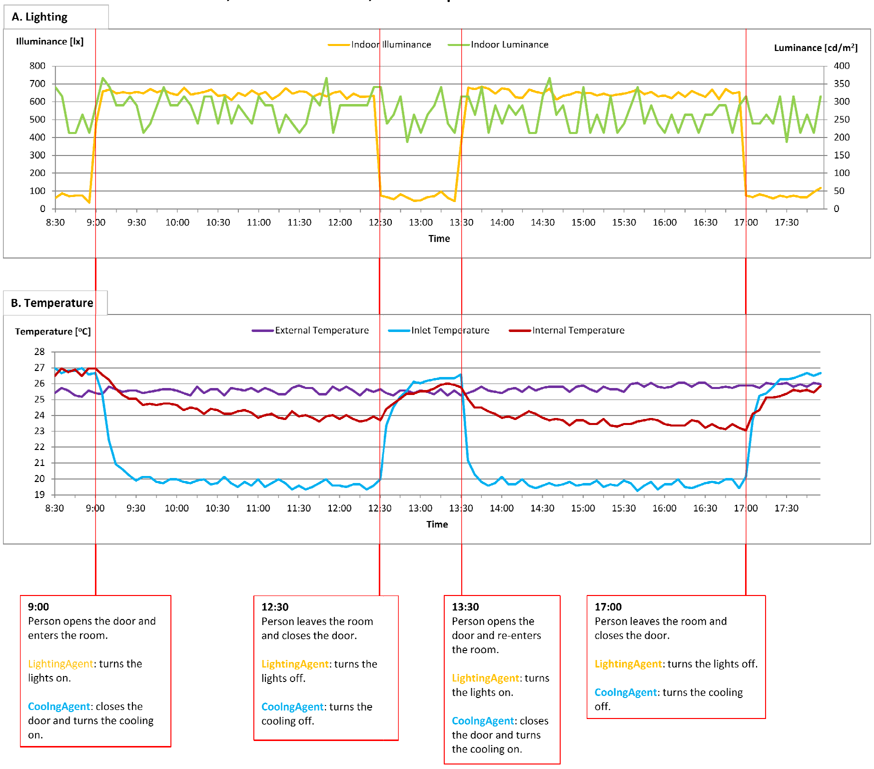


Figure E-14: Results of energy saver with MAS control. This scenario represents a regular working day in summer. The person working in the room is someone who tries to save energy whenever possible. The blinds are static and are always fully down. The person enters the room at 9:00, sets the thermostat to 22 °C and leaves for home at 17:00. Between these hours he never has to turn the cooling or lighting on or off, because the MAS automatically takes care of it.

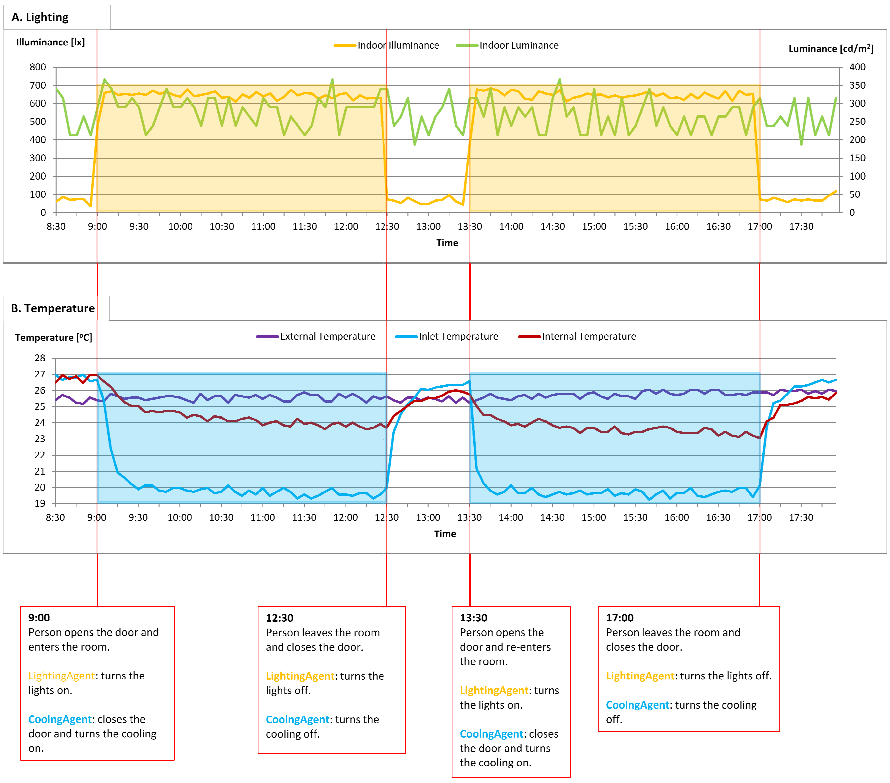


Figure E-14a: The same as figure E-14a, except this time the lighting and cooling loads are included in the graphs.

Scenario 4.3

User: energy saver, preferred temperature 22 °C

Control: MAS control, dynamic blinds, static price

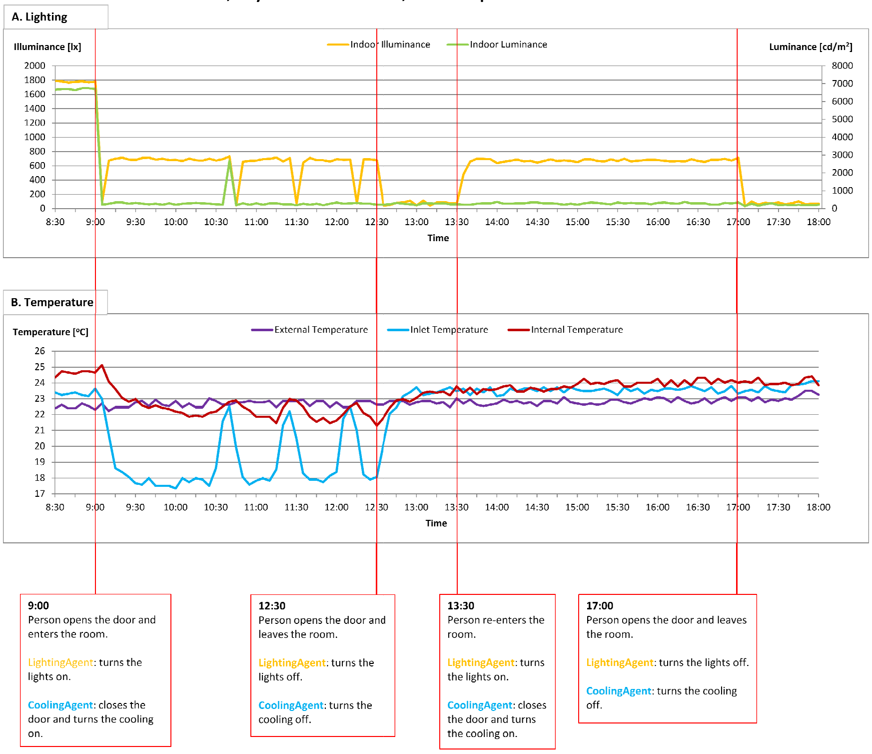


Figure E-15: Results of energy saver with MAS control and dynamic blinds. This scenario represents a regular working day in summer. The person working in the room is someone who tries to save energy whenever possible. The person enters the room at 9:00, sets the thermostat to 22 °C and leaves for home at 17:00. Between these hours he never has to turn the cooling or lighting on or off and never has to raise or lower the blinds, because he can fully rely on the MAS for the control of all these three systems.

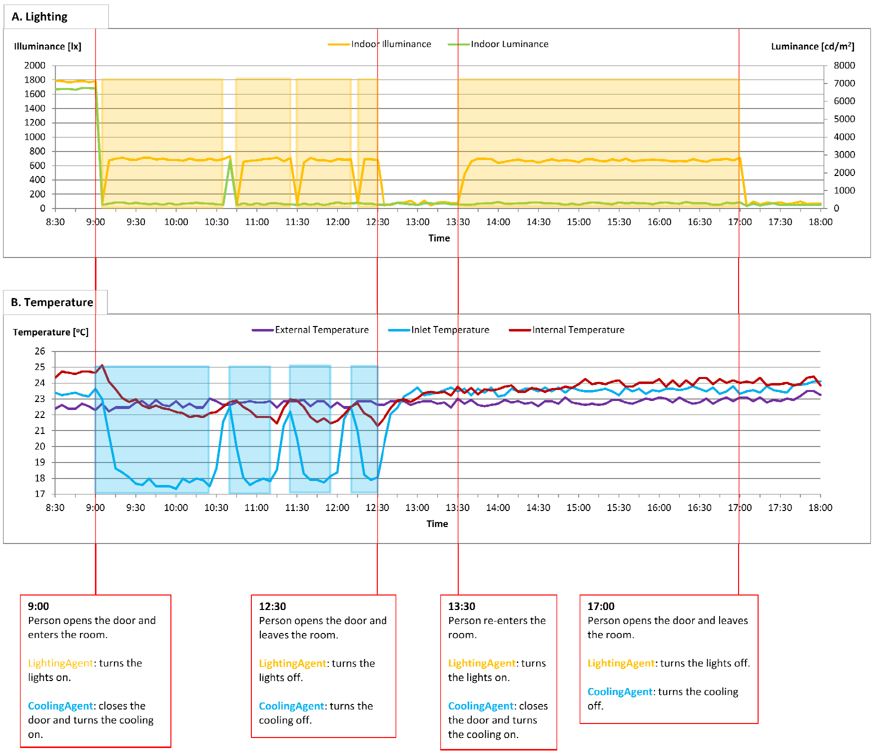


Figure E-15a: The same as figure E-15, except this time the lighting and cooling loads are included in the graphs.

Scenario 4.4

User: energy saver, preferred temperature 22 °C
Control: MAS control, dynamic blinds, dynamic price

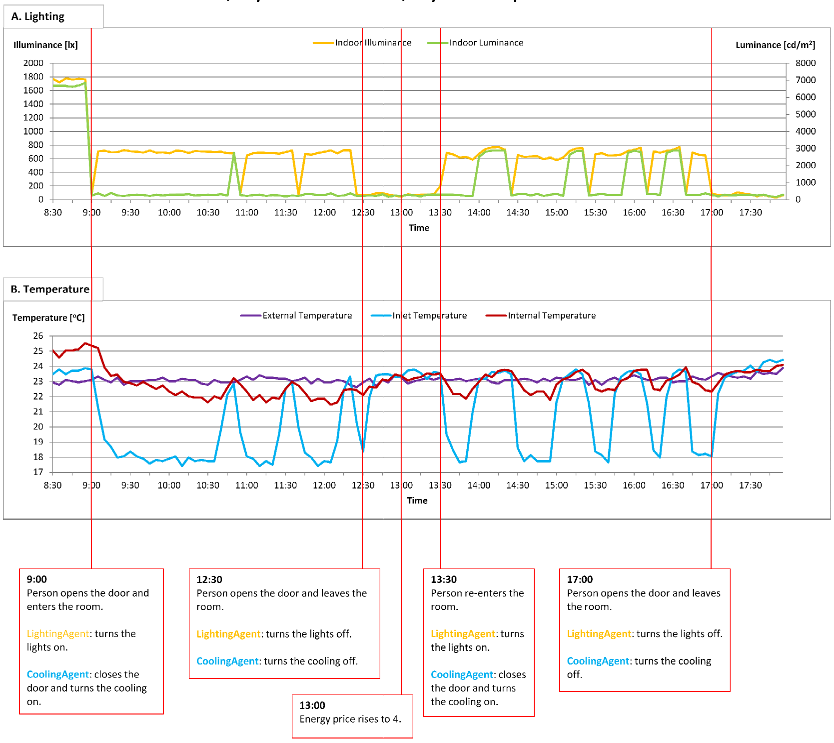


Figure E-16: Results of energy saver with MAS control, dynamic blinds and a fluctuating energy price. This scenario represents a regular working day in summer. The person working in the room is someone who tries to save energy whenever possible. The person enters the room at 9:00, sets the thermostat to 22 °C and leaves for home at 17:00. Between these hours never has to turn the cooling or lighting on or off and never has to raise or lower the blinds, because he can fully rely on the MAS for control of all these three systems. In the morning the energy price is 2 and in the afternoon the energy price is 4.

Figure E-16a: The same as figure E-16, except this time the lighting and cooling loads are included in the graphs.