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TRABAJO FIN DE GRADO

DESIGN AND IMPLEMENTATION OF AN AGENT-BASED SOCIAL SIMULATION MODEL OF ENERGY RELATED OCCUPANT BEHAVIOUR IN BUILDINGS

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Eduardo Merino Machuca

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Resumen

El consumo de energía en los edificios representó el 20% del total de la energía consumida en todo el mundo en 2016. Además, este valor crece alrededor del 2% por año, y es más elevado en lugares como la UE, el 41% y los EE.UU, 40%. Por lo tanto, existe un creciente interés en las tecnologías que permiten la monitorización inteligente y el control de los equipos de los edificios para mejorar la eficiencia energética. Además, el número de personas que trabajan en interior, cuya productividad se ve muy afectada por su confort, está aumentando. Esto ha traído la noción de edificios inteligentes, que combinan el objetivo de ahorro de energía con la comodidad de los ocupantes.

Se ha demostrado que el consumo de energía en los edificios es influenciado en gran parte por el comportamiento de los ocupantes. La mayoría de los sistemas de control y operación de edificios en sistemas energéticos consideran modelos basados en horarios, comportamientos y preferencias generales de los ocupantes que conducen a grandes errores predictivos y de optimización.

En este trabajo se propone un nuevo modelo de eficiencia energética basado en una simulación multi-agente y la aplicación de metodologías. El comportamiento de cada ocupante es modelado mediante estados, de acuerdo horarios definidos y un proceso de decisión Markoviano. El equipamiento eléctrico, el sistema de iluminación y los sistemas de aire acondicionado se modelan como agentes pasivos y reactivos. Las operaciones del entorno simulado se regulan mediante tres estrategias de control o políticas distintas que implican diferentes niveles de operación inteligente. Los resultados de confort y energía obtenidos son evaluados y valorados

Como resultado, se obtiene un 13.28% de reducción en el consumo de energía y una mejora del 11.03% en el confort de los ocupantes como comparación entre la política tradicional y la más avanzada.

Palabras clave: Consumo de energía, Sistemas multi-agente, Simulación de ocupancia, Políticas energéticas, Edificios inteligentes.

Abstract

Energy consumption in buildings accounts for 20% of the total energy consumed worldwide in 2016. Furthermore, this value grows around 2% per year and is higher in place such as the EU, 41%, and US, 40%. Thus, there is a growing interest in technologies that enable intelligent monitoring and control of buildings' equipment to improve energy efficiency. In addition, the number of indoor workers, whose productivity is greatly affected by their comfort, is increasing. This has brought the notion of Smart Buildings, that combine the energy saving with the occupants' comfort goals.

Energy consumption of buildings is proved to be largely influenced by the presence and behaviors of occupants. Most systems of control and operation of buildings in energy systems consider general models based on general occupants' schedules, behaviors and preferences that leads to large predictive and optimization errors.

A novel energy efficiency model based on multi-agent occupancy simulation and methodologies application is proposed in this work. The behavior of each occupant is modeled by states according to schedules and Markov decision process. The electrical equipment, lighting system and air conditioning systems are modeled as passive and reactive agents. The simulated environment's operations are modeled by three distinct policies or control strategies involving different levels of intelligent operation. The obtained comfort and energy results are evaluated and valued.

As result, a 13.28% reduction in energy consumption and a 11.03% improvement in occupant comfort are obtained as comparison between the traditional and most advanced policy.

Keywords: Energy consumption, Multi-agent systems, Occupancy simulation, Energy policies, Intelligent buildings.

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Quiero dar las gracias a mis padres, Pedro y Alicia, por motivarme a ser capaz de todo, en especial durante esta carrera, pero también durante toda mi vida como estudiante.

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CHAPTER 1

Introduction

There is a crucial need to reduce energy consumption in all fields. The negative environmental impacts of rapidly growing world, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc), have originate international initiatives, such as the COP21, and European ones, such as 20/20/20, which have a fundamental objective to achieve countries to reduce their energy consumption. In addition, small and large business owners seek to reduce costs.

Energy consumption in buildings accounts for 20% of the total energy consumed worldwide in 2016 [28]. Furthermore, this value grows around 2% per year [28] and is higher in places such as the EU, 41% [13], US, 40% [4], or China, around 27% [22]. Buildings energy consumption can be reduced by many and different sources, such as the equipment's efficiency and the building materials. However, energy consumption of buildings is proved to be largely influenced by the presence and behaviors of occupants [42]. Thus, there is a growing interest in technologies that enable intelligent monitoring and control of buildings' equipment based on occupancy to improve energy efficiency. In addition, the number of indoor workers, whose productivity is greatly affected by their comfort [34], is increasing. Both building energy consumption and occupant comfort are two critical parameters that can be monitored and controlled in Smart Buildings for improvement.

Nowadays, there is a significant uncertainty caused by occupant behaviors that produces notable discrepancy between the predicted and actual energy usage. People affect the performance of buildings due to their presence and their actions, effect called as 'performance gap' or 'rebound effect' [25]. In the real world, most systems of control and operation of buildings in energy matter consider general models based on occupants' schedules and imprecise behaviours that leads to large predictive and optimization errors. The static and homogeneous modelling leads to a lower accuracy in predicting building energy performance. Traditional buildings lack of real-time acquisition systems of variable information relating with occupancy actions, decisions and preferences. In some cases, movement based sensor-systems, or similar, used to obtained this information are installed. However, current systems lack intelligent monitoring, with computer support, that enable a controlled, quick, acquire and adaptive response. Besides technology, new policies and strategies must be generated and implemented to a proper establishment. The occupants' behavior relevance, the technological agents performance and the interaction between them are modified according to that policies.

The implementation and utilization of a based-on multi agent simulation software is presented in this work. The goal of show alternative management and control systems that manage a energy use reduction and increase the occupant comfort is achieved by the simulation of agents acting in a realistic environment. Computer equipment, lights and Heating, ventilation and air conditioning (HVAC) system are, in accordance with the policy, the passive or reactive agents that define the electrical system. The space is defined by thermal zones, thermal loads, rooms, temperatures, windows and doors. The environment is implemented with data from real-world building; specifically, a university second floor where there are professors and researchers working and two classes. Each occupant is characterized by their own temperature preferences, locations, schedules, activities and environment behaviors. The occupant's actions are implemented by finite-state machine controlled with the schedules and with Markov decision processes (MDPs).

The operations in the building are simulated according three distinct control strategies or policies. First, traditional buildings' environment are implemented as Baseline. Second, intelligent presence sensors that can control the lights, equipment and HVAC system are added as Reactive strategy. Finally, the intelligent control of the HVAC system is improved, enable to be configured by the occupants' schedules and preferences. This last one is the Proactive strategy.

1.1 Project goals

The goals of the presented simulation software and this project are (1) to provide a realistic and predicable tool useful for evaluating and managing methodologies for energy building consumption reduction (GreenSOBA), which is available as open source [1], (2) to propose strategies to optimize the relation between energy consumption and occupants' comfort and (3) to present and to evaluate the obtained results with each of these strategies.

As an intrinsic goal, a system of simulation of occupancy based on agents (SOBA), which is useful for conducting studies based on occupancy simulations in buildings, such as drill simulations, is implemented and provided as open source software [27].

1.2 Structure of this document

In this section, it is provided a brief presentation of each chapter included in this document.

1. **Introduction**. The background and the project goals are presented.
2. **Enabling technologies**. The systems or tools used to implement this project are described.
3. **Simulation model**. The modeling designed to achieve the proposed objectives is defined.
4. **Architecture**. The implementation required to recreate the modeling is described.
5. **Results**. The project outcomes are presented and analyzed.
6. **Conclusions**. The consequences of the results are valued.

1.3 Background

1.3.1 Occupancy simulation and building energy consumption

Currently, there exists various building performance simulation tools capable of realizing accurate infrastructure and energy studies in buildings based on a description from the precise perspective of the building's physical make-up and associated mechanical systems, such as TRNSYS [8] or EnergyPlus [17]. A number of research [19, 33] has analysed the impact of the design and the building materials in the comfort and energy performance. As a result, optimization strategies have been published as well as tools such as EnergyPlus.

Nevertheless, in these tools the occupancy is either defined with only fixed schedule or not considered. Some studies regard a software framework by means of the combination between a buildings tool with a programming script. For instance, [7] proposes the use of a predictive model to minimize the energy demand thanks to the application of optimal control strategies of the HVAC system, and implements this predicting system by combining EnergyPlus and a heuristic algorithm implemented in MATLAB. The predictive model is based on fixed occupant profiles considering Boolean occupancy (occupied or vacant), performance in a residential building with three areas, and on forecasts of climatic conditions, optimizing function to foresee the thermal loads and to modulate the instant thermal input supplied by the active energy systems, with the aim of increasing energy efficiency and thermal comfort.

Multi-agent systems (MAS) are frameworks that contain agents and objects performing operations in an environment [16]. MAS are used as a solution to model occupancy related complex problems by real world performance-based simulations. In addition, intelligent elements, such as sensors or smart equipment, can also be modeled as agents together with the occupants, enabling communication and coordination with each other as well as with the environment. MAS have been very employed recently in software for occupancy and building energy and comfort research. Because of their complexity, articles focused on detailed occupancy models, simulated [24] or based on occupant monitoring and data collection with sensors psychical [43] are published. As a result, occupancy diversity factors and patterns have been published, being useful to support acknowledge basis to defined occupancy agents behaviour in this work' simulation. A number of papers [24, 43, 40] propose a better representation of random occupancy presence and behaviour through stochastic models, emphasizing inhomogeneous Markov chain, together with occupant profiles, in contrast with conventional static schedules.

Moreover, other works [41, 10, 21] are focused on energy saving and occupant satisfaction through value added services provided by a combination of sensors, intelligent embedded agents and actuators, that control room characteristics such as temperature and lights, according to occupant preferences. They propose several policies to improve the efficiency of HVAC and electry system operation, which are described below.

Yang and Wang [41] presented a MAS model that interacts in an environment with lighting and HVAC. This system is based on three kinds of agents: central agent, local agent, and personal agent, which operate as main control system, control of room elements and occupants. In the Davidsson´s research [10], the customer satisfaction is realized by temperature and light intensity regulation in function of each person´s personal preferences, while energy consumption is reduced by lights being automatically switched off, and room temperature being lowered in empty rooms. The psychical properties related with building temperature are modeled through the thermal resistance and capacitance, simplification to describe the thermodynamical characteristics of a room. The MAS is operated by four different policies: (1) thermostat´s temperature constant, (2) controlled by timer, (3) reactive sensor that reduces the temperature of the empty rooms and (4) based on occupants´ preferences. Almost 40% energy reduction was achieved with the first two policies, maintaining the average temperature occupants´ satisfaction.

Another work [21] describes a simulation software, so called MACES, to manage and coordinate input from human and building system. This system is employed to reduce building energy and increase occupant comfort by means of four strategies: (1) baseline, current building management system, (2) reactive, HVAC, lighting, and appliance to occupancy, (3) proactive, adjust according to predicted occupancy, and (4) proactive-MDP, meeting relocating by specialized agents.

Occupant behaviour is modelled through Markov Decision Problems in combination with wireless sensor network (WSN) systems. In addition, they propose the use of thermal loads for modelling the HVAC system. Among the factors included for calculating thermal loads, they consider solar gains, windows' effects and equipment and occupancy gains in a room at a given time. The authors report savings that range from 4.46% (reactive policy), 6.86% (proactive policy) to 12.17% (proactive-MDP policy). Moreover, all strategies report 90-95% of satisfaction levels.

1.3.2 HVAC system

It is interesting to highlight the rising number of research on intelligent HVAC systems, related with MASs, due to their weight, around 40% - 60%, in the building energy consumption [31], and in the occupants' comfort [42], determined by three basic factors: thermal comfort, visual comfort, and indoor air quality comfort [41]. Two of these factors are mainly controlled through HVAC system and one through lighting system. The proper modeling of an intelligent HVAC system is a more complicated challenge than the regulation of the equipment and light system, because of its higher complexity. Dobbs and Hencey [11] employed a physical sensor system to generate an occupancy predictive control model based on Markov chains by a Bayesian training, considering Boolean occupancy, to reduce the HVAC energy consumption. The thermal modelling is modelled with a simplified methodology, Resistance-Capacitance Modelling ToolBox [37], as previously proposed by Davidsson et al. [10]. Tree implementations are presented: (1) scheduled, (2) scheduled supplemented with occupancy triggering and (3) predictive control with one week of pretraining. They report 27% energy saving with the occupancy triggering strategy and 19% with the predictive control strategy.

In relation with HVAC systems, modeling techniques are divided into three: data driven, collecting data using physical performance; physics based, using a detailed representation of the governing laws of thermodynamical physics; and grey box models,

In relation with HVAC systems, modeling techniques are divided into three [3]: *data driven*, collecting data using physical performance; *physics based*, using a detailed representation of the governing laws of thermodynamical physics; and *grey box models*, employing combination of the previous methodologies. In addition, as it is described in the review, each technique has various models. The RC (resistive-capacitive) method, belonging to grey box model and represented by a RC circuit, was used in [10, 11], since both investigations employed data mining through physical sensors. In contrast, in [21] was adopted the zone model, belonging to physics based models, constructed on a heat balance method, since only virtual simulation was used.

The zone model based on physics models is used in this work' software simulation. One of the main advantages of the zone model based on heat balance method is the absence of model intrinsic assumption [10, 11]. This model simplifies load calculation and enables the interaction with a variety of complex elements to model physical phenomenons, providing clarity and modularity [36]. In relation to this, more flexibility is provided to the simulation software implemented in this work, which is available as open source [1], enabling to define new operating ways.

1.3.3 Building management system

Control policies or strategies are a key factor to develop building energy research. Their main purpose is the evaluation of different operating models in buildings for assessing on their energy impact as well as on the occupancy satisfaction. Based on several articles that apply MAS for energy optimization in buildings [21, 41], we classify these policies in four types, presented in order of complexity: (1) Standard or Baseline, occupants employ on/off switching controllers and thermostats have a temperature constant value, (2) Reactive, changes are automatically produced in response to occupant actions or modifications in physical characteristics, (3) Proactive, response is predicted with initiative, and (4) Social ability or Interaction, there are communication and coordination between occupants and the building management system.

Other papers [9] propose a different approach to policies, for instance, centred in a business view, where a demand response strategy, based on a consume adaptation in function of economic means such as dynamical pricing by means of being able of receiving real-time energy pricing information together with the states of various building systems to adjust building-wide energy usage, is used.

The listed above strategies Baseline, Reactive and Proactive are used in the simulation model described in this work. Besides, an adequate technological selection is required in order to apply these policies and to provide reachable results in the reality.

Current building management system (BMS) generally operate according to centralized systems, configured by generic and imprecise parameters, and distributed elements, mainly controlled by the occupants.

Centralized HVAC systems' operational settings are typically designed considering the known occupied and unoccupied periods of the day, based on fixed schedules. Nevertheless, they do not consider other factors, such as intermediate periods with building partially occupied [42], as well as different occupant preferences [20]. The distributed equipment, such as computers and illumination, operate according to unpredictable occupants behavior. Both are generally passive systems without the capacity to react (reactive) or to predict (proactive) aimed to optimize the use of equipment in terms of consuming and performance. Occupancy sensor technology is required to provide these functionalities. However, occupant detection technologies such as PIR [23], microwave [39] and ultrasonic [6] usually commit errors [12], and others as detection with cameras have serious privacy issues [29]. Besides, an intelligent interaction system between the occupants and the BMS is not implemented with these technologies, limiting hugely the reactive and proactive capabilities.

Recent research has demonstrated a large potential with regard to the WSN technology to provide a smart monitoring and control system toward the implementation of an intelligent building, whose BMS can be controlled and programmed from a local server web page [38]. The combination of web and mobile applications is another trend for providing accurate and intelligent BMSs [35]. These mobile BMSs combine reactive and proactive approaches, and integrate the configuration of occupants preferences as well as tracking their presence. This is the technological model adopted in the simulation software described in this work through which the selected control policies can be modelled in the simulation.

CHAPTER 2

Enabling Technologies

2.1 Introduction

In this section, the technologies and tools used in to implement this project are described: the Python ecosystem 2.2, the open source MAS simulation package Mesa 2.3, and the auxiliary package Transitions 2.4 for modelling state machines.

2.2 Python

This project has been implemented with Python [30], which has become an increasingly popular language for scientific computing, supported by a mature and growing ecosystem of tools for analysis and modelling. Some of the advantages of Python are its support of multiple systems and platforms, its scalability, its extensive ecosystem of libraries and the community support. Besides, an interactive analysis of model output data is also provide by Python, through the IPython Notebook.

2.3 MESA

Mesa [26] is an open-source software useful to create agent-based models with the programming language Python. Mesa's architecture is defined with modularity. Mesa provides four different modules, which are used in the implementation described below as a basis element to initiate and to control the simulations.

1. The *Model* is the core of the simulations. The class Model stores model-level parameters and serves as a container for the rest of components. Besides, it provides a scheduler that controls the agent activation regime.
2. The *Agent* class provides an extensibility mechanism to define agent behaviors in simulation models.
3. The *space* where the agents are situated and where they perform their actions, which is defined by means of a grid with coordinates (x, y).
4. *Visualization* component that provides a simple mechanism to represent the model in a web interface, based on HTML rendering though a server interface, implemented with web sockets.

Mesa is the package used as the basis for implement our system of occupancy based on agents (SOBA). This system is described in Chapter 4. The main extensions provided by SOBA are a module of energy policies and a module for modelling occupancy in buildings.

2.4 Transitions

Transitions [2] is a lightweight, object-oriented state machine implementation in Python. Besides the definition of state and the transitions associated with them, other interesting functionalities are provided. A useful feature is to define methods or functions that are run during the transitions. The states are also associated with a list of 'enter' and 'exit' callbacks, which are called when the state machine enters or leaves a state. In addition to this, it is also possible to attach callback functions with a 'before', of exit a state, and 'after', of entering a state, attribute. All agents' states are defined and controlled with this package.

However, as previously presented, we propose to employ MDP for modeling the transitions between occupants' states. This crowd behaviour has been packaged as a module as described in Sect. 4.2.2.

CHAPTER 3

Simulation Model

3.1 Introduction

In this section, the components designed to model the environment and the actors, which provide a suitable simulation system, are described. Firstly, an overview is presented. Secondly, the system central or model, which makes the control and the physical elements modeling, is described. Thirdly, space, where is performed the simulation, is defined. Finally, all the simulation performing actors are presented and characterized.

3.2 Overview

The modelling of the environment and the agents is made following the diagram of components as shown in Fig. 3.1. The main modules are: (1) the **agents**, which represent the occupants, the equipment, the HVAC and the lighting system; (2) the physical **space**, which is formed by the building rooms; (3) a **model** or central control component, which initializes and controls the simulation following the defined parameters and the policies or control strategie; and (4) the **physical phenomena** of energy consumption and the thermal load gain and loss. In addition, (5) a **agent behavior** model component is implemented, which includes the state machine used by all agents and the Markov chain used to simulate a realistic occupancy behavior in building. Finally, there are a (6) **configuration** component, which enables to characterize the behavior of the agents and the physical environment, and a **visualization** component, which represents the simulation in real-time and the results generated by each policy.

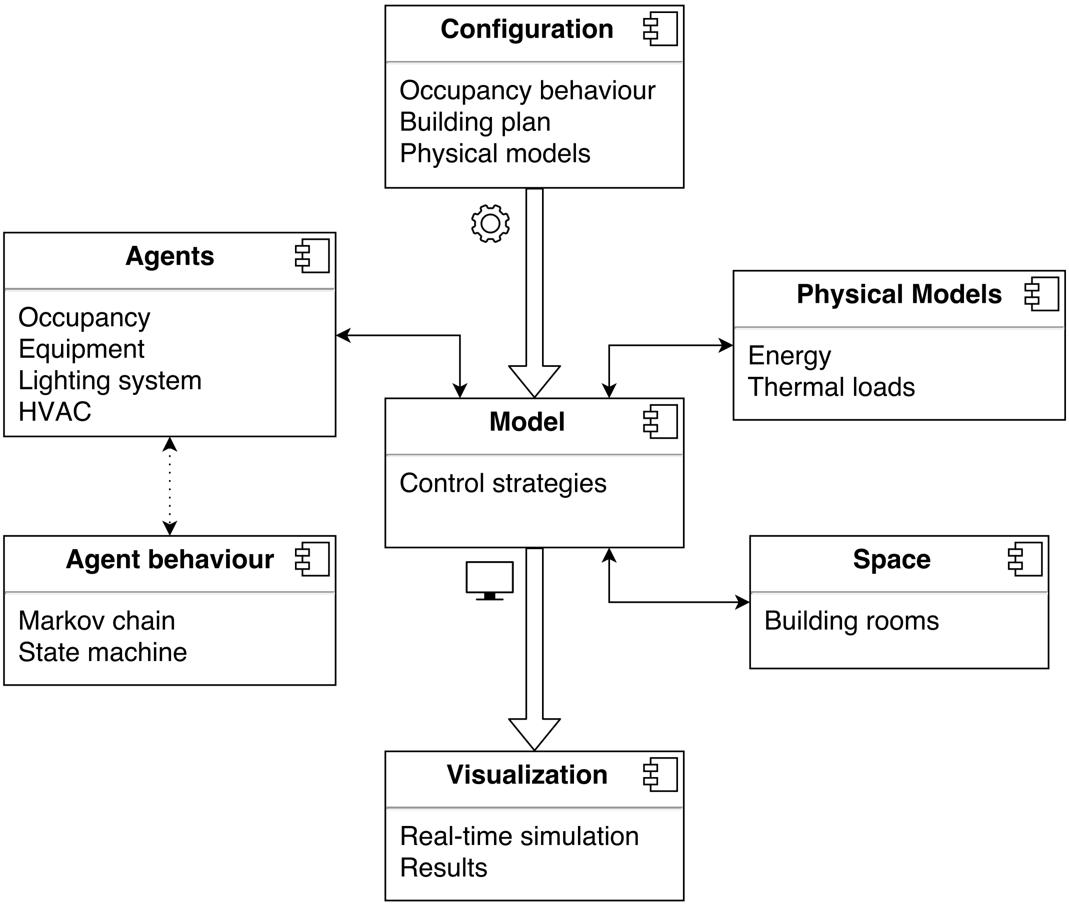

Figure 3.1: Components of the Simulation Model

3.3 Model

The **Model** is the simulation epicenter, most interactions are made through him. The main tasks of the Model are the initialisation of the simulation, which includes the Space (i.e. floor plans of the building) and the Agents, both human agents and energy based agents, such as Lighting and HVAC. In addition, the model manages the building energy consumption, the physical model of temperature variation and thermal load exchanges, as well as the evaluation of occupant satisfaction. A number of strategies or control policies are used to adjust or modify the occupants energy behaviour.

The operation of the model and the agents is regulated by means of these control strategies or policies, which modify the interaction methodology between agents and their performance in the building. This enables to make simulations under different conditions, which reflects distinct technological and social models in buildings, obtaining diverse results that can be contrasted and evaluated. Three different policies have been designed and implemented, which are described below.

1. **Baseline**, used as the reference of the current method of operation in most of the buildings, represents the situation to improve.
   (a) The *equipment* is mainly controlled by the occupants, who turn on, turn off and set standby their assigned appliance. However, the standby mode is automatically set after a few minutes.
   (b) The *lighting system* is only switched manually by the occupants, but it is switched off in all building's rooms after 11 PM.
   (c) The *HVAC system* is programmed to operate during a wide fixed schedule and with a constant temperature: 24ºC.
2. **Reactive**, strategy by which a system capable of responding to the activity of the occupants is modelled.
   (a) The *equipment* is controlled automatically un function of the proximity of the occupant assigned to that equipment and the time.
   (b) The *lighting system* is switched on and switched off by means of high accuracy occupancy presence sensors.
   (c) The *HVAC system* is programmed as in the Baseline strategy, but is added a new operation based on high accuracy occupancy presence sensors, which enable to increase the desired temperature in a room to 27ºC when it is unoccupied during a considered period.
3. **Proactive**, policy by means of which the building management system has the ability to take the initiative and make self-configurations by predicting the occupancy behavior, using information obtained from a previous log.
   (a) Both *the equipment* and the *lighting system* are controlled as in the Reactive strategy
   (b) The *HVAC systems* employ intelligent sensors to generate logs with data on occupancy schedules. This information is used by these systems to self-define their own operation schedule, which can be auto-adjusted in response to unexpected events, such as overtime. Additionally, a new functionality by which the occu-

pants can select a preference temperature own, which is used to make a voting and choose the room temperature, is provided by HVAC systems. The room temperature provided by an HVAC system is determinated using social choice theory. In particular, a voting strategy is used for maximising the occupants comfort.

3.4 Space

The **space** where take place the simulation is formed by rooms, which are characterized by a width, length, height, number of windows (and their size), a type (office, corridor, laboratory, class, hall or restroom), inner and external walls, and the connexion between them, where doors are positioned. Some of these elements are not relevant for the simulation of occupants and energy per se, but they are employed for the thermal model. All the rooms, except the restroom, belong to a thermal zone, which can be associated with more than one room. The model manages all the movements of occupants as well as their interaction with equipments and lighting systems.

Our system has been evaluated in the ETSIT Telecomunicación of the Universidad Politécnica de Madrid. In particular, we have modeled the second floor of the building B, as shown in Fig. 3.2. This floor has a rectangular shape and an area of 1600 m2 ($\sim$16x100m). In order to understand occupants behaviour, a survey has been submitted and processed, so that the simulation can exhibit realism. In addition, we have contacted the maintenance department of the building to collect energy related information based on that we have developed a model of thermal zones distribution.

The building is formed by four types of room: offices, laboratories, classes and transition spaces, such as halls, corridors or resting areas. The occupation is medium in offices (1-5 professors) and laboratories (3-8 researchers); low in transition spaces; and high in classes (30 students). The floor is divided into 41 rooms and 32 thermal zones, distributed as 14 offices, with one thermal zone by office, 20 laboratories, with 12 thermal zones, 4 classes, one thermal zone by each one, and 1 hall and 2 corridors, divided in 2 thermal zones. In addition to this, there is one restroom, which does not belong to any thermal zone. There are two available exits, one to exit from building and another to enter to other connected building.

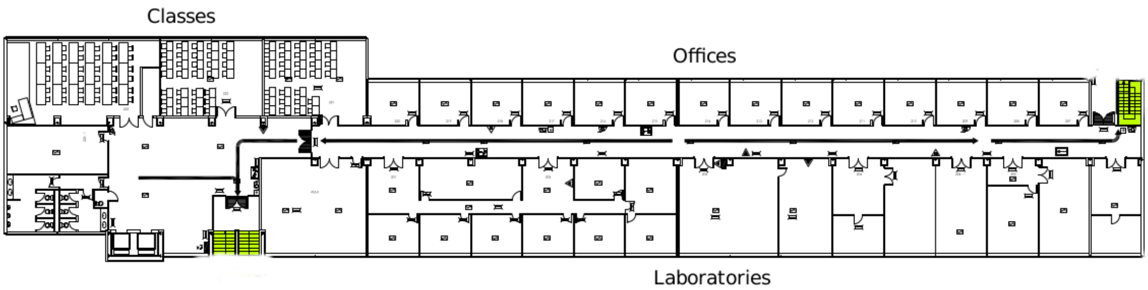

Figure 3.2: Building plan

3.5 Agents

While the control of the simulation is a responsibility of the Model, the simulation performance is made by the **agents**. Agents have been modeled using probabilistic state machines. Each state represents an agent's task. Energy effiency policies have been modeled in these state machines. For example, occupants can switch off lights (or not) when they go out of their offices. In the same way, lighting agents can activate the light based on presence sensors if they apply the reactive or proactive strategy.

3.5.1 Occupants

The behavior and activity of the occupants in the building are represented through **occupancy agents**, which are divided into three kinds: professors, researchers and students. All occupants are defined by various states with positions, a schedule, an environmental behavior and a preference temperature. The states are the main engine to model the daily activity of people in a building. These, and the place where are performed, change with each occupant type as described in Table 3.1.

The occupancy agents performance in the building is controlled by the simultaneous action of schedules and Markov decision problems (MDP), triggering the transitions between states and defining the time in each one. Some states' triggers are adjusted with the equation below, in which is considered an average hour plus a deviation,

$$P_t = \frac{P_a * T_i}{T_2 - T_1} \tag{3.1}$$

where P_t represents the probability of transition during one evaluation, P_a the expected percentage agents which made transition in each evaluation, T_i the time interval between evaluations and T_1 and T_2 the start and end of the transition evaluations.

Agent type	*Number*	*State*	*Place*
Professor	40	Out	Outside building
		Working	Offices
		In a metting	Laboratories
		Giving class	Classes
			Outside building
		Having a break	Hall
			Outside building
		Having lunch	Outside building
Researchers	40	Out	Outside building
		Working	Laboratories
		Having a break	Hall
			Outside building
		Having lunch	Outside building
Studients	125	Out	Outside building
		In class	Classes

Table 3.1: States and position associated by occupant type

Each evaluation of a possible change of state is made one or more than once and after more or less extensive periods, increasing or decreasing the randomness, according to the known occupancy schedule. As a result, a Discrete uniform distribution is obtained, which models a variable and realistic schedule. States more predictable, such as arriving, leaving or going to lunch, are defined in this way. All other states, which take place in the building, are stochastically operated by means of Markov chains, which are executed when each duration time associated with the current state is ended. The duration of with each state is defined using real information plus a random variation.

An occupancy agent interacts with the other agents by using the equipment, turning off and on the lighting system and exchanging information with the HVAC system, although these operations change in function of the policies. The decision to turn off, put in standby or let on the equipment and to turn off or let on the lights changes in function of the situation and from one person to another. This is modeled as three different environmental attitudes or behaviors in the simulation: excellent, good and bad. The percentage of each type of occupant belonging to each of these behaviors is described in Table 3.2. Also, it is considered as environment behavior the decision to close a door or let it open, which is relevant in the HVAC system consumption.

Type of	Enviroment behaviour (%)			Number of time door is closed	
occupant	Excellent	Good	Bad	Variation	Average
Professors	25%	65%	10%	70 - 95%	90%
Researches	35%	60%	5%	70 - 90%	85%
Studients	10%	60%	30%	60 - 90%	75%

Table 3.2: States and position associated by occupant type

Finally, it is essential to define temperature preferences that are exchanged with the HVAC system in the proactive strategy, which are different between occupants. These are randomly generated obeying a variation of 19.0°C to 26.0°C and an average of 22.8°C.

The information on the routine or the daily activity is obtained from a survey completed by 13 professors and 12 researchers who work in the studied university's floor and knowing the classes schedule. Besides, the different states assigned to each kind of occupant, the place when are performed these activities and their duration, the occupancy environmental behavior and temperature preferences are known also employing this survey.

3.5.2 Comfort evaluation

There are important differences between the temperature preference of one person and another, which is showed in the results obtained from the survey. This variation also appears in the way in which is increased the dissatisfaction or discomfort degree produced by the room temperature variations with respect to the personal preferences, and this fact complicates to make a representative of reality occupant satisfaction evaluation.

In this project, two methodologies have been used. The first one is known as the **Fanger's method** [15, 14], that is perhaps the most commonly cited experiment on the human perception of thermal comfort have been performed. According to this method, the level of activity, the clothing characteristics, the temperature, the relative humidity, the mean radiant temperature and the air velocity are the main factors which, by influencing in the thermal exchange between human-environment, determine the occupant comfort or satisfaction. The result is presented as the uncomfortable people percentage in a determined environment and is obtained from the graph presented in the Fig. 3.3. It has been defined experimentally and is represented by the equation located above the graph.

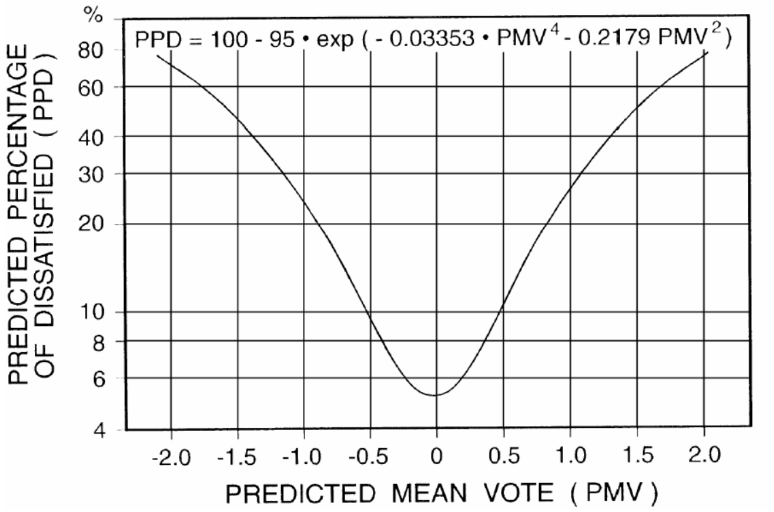

Figure 3.3: Fanger's Method [15]

The coordinate x value, known as PMV (predicted mean vote), is given as result of the evaluation of before named variables. In order to calculate PMV, an approximation method, so called ISO 7730 approximation method, based on tables, has been used, instead of following the exact analytical method, which requires solving complex equations. The chosen values for the variables have been generalized for a Summer month. These variables and values are: an activity level of 120kcal, a clothing level of 0.75, a relative humidity of 40%, and air velocity of 0.15m/s. First, the value of PMV0 (predicted mean vote not rectified) corresponding to these conditions is obtained from the Table 3.3, which is provided in ISO 7730.

Temperature	18	20	22	24	26	28	30	32
PVM0	-1.49	-1.00	-0.48	0.04	0.56	1.09	1.62	2.17

Table 3.3: Based on tables Fanger's method approximation

Then, the final PMV value is obtained by adjusting the PMV0 value with the equation below,

$$PVM = PVM0 + f_h * (HR - 50) + f_r * (T_r - T_a) \tag{3.2}$$

where f_h and f_r are the correction factor of humidity, 0.008, and temperature, 0.13, HR is the relative humidity, T_a is the environment temperature and T_r is the mean radiant temperature, which is considered one degree more than T_a.

The Fanger's method provides a generic measure that could be obtained knowing only general environment and occupancy characteristics, which is really useful when individual occupant preferences are not known. However, satisfaction measures associated with a specific person, even knowing his preference temperature, can not be known. In this work, we propose a second analysis method, which consists of evaluating the occupants satisfaction. With this goal, we define a function that evaluate the difference among the room temperature and the occupants temperature preferences. This method aims at knowing the optimal temperature of a room based on the preference of their occupants, so that this temperature can be automatically set.

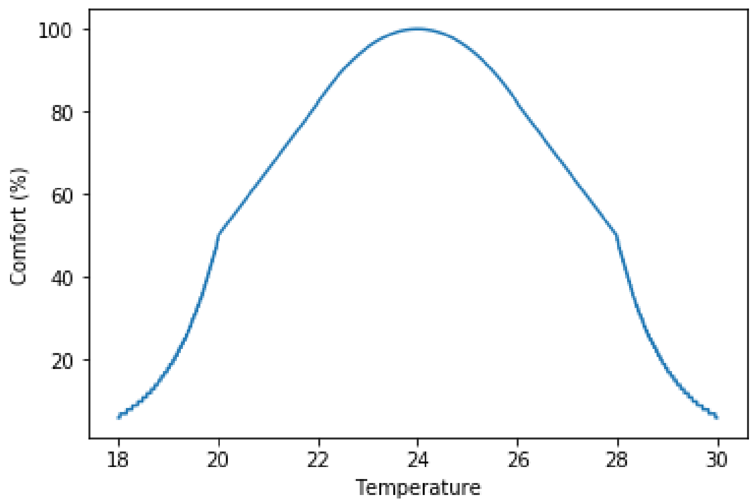

Figure 3.4: Proposed evaluation comfort method

The function used, which is presented in Fig. 3.4, is a piecewise-defined in which a variation in the temperature with respect to the occupant preference causes a rise of the dissatisfaction depending on the value of discrepancy. The values between 80% and 100% are good, in the range of 50% to 80% are acceptable but it should be improved, and lower than 50% are unsustainable results.

3.5.3 Equipment and lighting

The **equipment** represents the staff's personal computers, one or more than one are assigned to each occupant. Assignment is required for employing some policies. The energy performance is based on their state, which can be 'on', 'off' or 'standby'. This state is changed based on the actions of the occupants or autonomously, depending of the followed energy strategy.

The **lighting system** refers to the lights associated with each room, following the building plans. Lights are provided with presence sensors so that reactive and proactive policies can be followed. The lighting operation is managed with two states: 'on' and 'off', which are modified by the occupants activity or automatically if it is performed the corresponding strategy.

3.5.4 HVAC

The **HVAC agents** are assigned to the thermal zones, in relation one to one, controlling the rooms' temperature evolution during the simulation time. An intelligent sensor enables them to obtain and to use information on occupancy presence and preferences. Besides, both methods of occupancy comfort evaluation and control are operated by the HVAC. The performance is regulated by two states: 'on' and 'off', which are controlled by the model in function of the policies. Each HVAC systems is defined with a suitable power, which is the representation of energy (cool or heat) provided to the thermal zone air.

The three non-occupant agents are characterized by an energy consumption (W), which is used to calculate the energy consumption and the thermal contribution to the environment. The equipment consumes 75W on and 5W in standby and the light 432W on. In the case of the HVAC, this value is one-third of the energy power, which represents a usual performance.

3.6 Physical Models

A **timing module** must be employed, which is key to achieve a correct performance with aspects such as the occupants' behavior, the physical modeling and the energy consumption evaluation. It controls seconds, minutes and hours during all the simulation time: five labor days.

The **energetic system** registers the energy consumption from each source and classifies this information, enabling to obtain analyzable results. The report of this data, together with the values of occupants satisfaction, to be presented as graphs is made by the model.

The **heat balance method** is used in this project to calculate the heat and cold gains and losses of the building's thermal zones [32]. This operation is needed to model the temperature in a room and, by means of this, determine the occupancy comfort and the energy consumption associated with the HVAC system. The heat balance method calculation is based on the first law of thermodynamics, principle of energy conservation. Because of this, it requires fewer assumptions than other methods, being more flexible, and enabling to obtain competent result without the employment of external systems to the simulation, as physical sensors.

The operation is made separately in each thermal zone that can be formed by one or more different rooms sharing the same air mass. It has been considered the heat and cold transfers generated through equipment and lighting, occupancy activity, walls, inner walls, roofs, windows, air ventilation and air infiltration. We have selected building features and climatological considerations based on the real building. In addition, we have opted for the worst situations, such as considering a Summer month with higher occupation (i.e. July). All the technical values employed are obtained from ASHRAE Fundamentals Handbook [5]. Nevertheless, these operations could be also modeled under different conditions, such as Winter months, since required factors such as the reduced influence of the sunbeams during Winter months are also defined in the software. The equations used are described in the next points.

1. *Thermal conduction* through the roof, walls and windows:

$$Q = U * A * (T_i - T_o) \tag{3.3}$$

   where U is the thermal transmittance of the material, A the element area, T_i the temperature inside and T_o the temperature outside. In the calculation referring to inner walls, T_i and T_o are room temperatures of different thermal zone.

2. In Summer months, the effect of *convection*, *conduction* and *solar radiation* must be considered:

$$Q = U * A * CLTD \tag{3.4}$$

   where U is the thermal transmittance of the material, A the element area and CLTD the element cooling load temperature difference.

3. Solar load through *windows' glass*:

$$Q = A_s * maxSHGC * SC * CLF \tag{3.5}$$

   where A_s is the un-shaded area of the windows' glass, $maxSHGC$ the total solar heat transmission, a statistical data, SC the shading coefficient, determined by glazing product effectiveness (∼0.8) and CLF the cooling load factor.

4. Heat gain through *lighting system*:
   For a florescent, only a percent part of the consumed energy generate light, the rest is converted to heat,

$$Q = (1.2) * (L_{ef}) * W \tag{3.6}$$

where L_{ef} is the light efficiency($\sim$25%) and W the power (watts).

5. Heat gain through *equipment*:

$$Q = F_u * F_r * CLF * W \tag{3.7}$$

where F_u is the usage factor, which is considered unit value, F_r the radiation factor, which is given by the equipment efficiency ($\sim$50%), CLF the cooling load factor ($\sim$0.8) and W the power (watts).

6. *Occupancy* loads:
The heat gain by the occupants in the building is separated into sensible heat:

$$Qsensible = N * SHG * CLF \tag{3.8}$$

where N is the number of people in the thermal zone, SHG the sensible heat gain per person (50W) and CLF the cooling load factor($\sim$0.8); and latent heat:

$$Qlatent = N * LHG \tag{3.9}$$

where N is the number of people in the thermal zone and LHG the latent heat gain per person (40W).

7. Thermal exchange through *ventilation and infiltration.*

   (a) An outside air entrance for maintaining occupant health and comfort is required:

   $$Q = \frac{ACH * Vol_{air} * \rho_{air} * C_\rho * (T_i - T_o)}{D} \tag{3.10}$$

   where ACH is the air changes per hour (4), Vol_{air} the total air volume in thermal zone, ρ_{air} the air density (1.19kg/m^3), C_p the air specific heat (1012J/kg*K), T_i the temperature inside, T_o the temperature outside and D = 3600 second/hour.

   (b) The infiltration is a small value and difficult to obtain. Only exchanges by open doors are considered:

   $$Q = 1.08 * CFM * \Delta T \tag{3.11}$$

   $$CFM = V * \frac{h * w}{2} \tag{3.12}$$

   $$V = 100 * \frac{\sqrt{h} * \sqrt{\Delta T}}{\sqrt{7} * \sqrt{\Delta T}} \tag{3.13}$$

   where h is the door's height, w the door's width and ΔT the temperature difference between rooms.

The sum of all this load as watts is used to simulate the thermal behavior model in the rooms, by means of the *first thermodynamic law* and *specific heat equation*,

$$\Delta J = J_{HVAC} - J_{Qload} \tag{3.14}$$

$$\Delta Tr = \frac{J}{C_{\rho} * Vol_{air} * \rho_{air}} \tag{3.15}$$

where ΔTr is the temperature increase or decrease in the thermal zone, Vol_{air} the total air volume in the thermal zone, ρ_{air} the air density (1.19kg/m^3), C_p the air specific heat (1012J/kg*K), J_{HVAC} the Joules provided by HVAC system and the J_{Qload} the total Joules obtained from thermal load exchange, that is, the result of applying the above equations.

All the values used in the modeling which are not specified in the equations above are defined in the tables below.

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Outdoor temp.(°C)	25	25	24	23	22	22	22	22	23	23	25	27	30	33	35	33	36	34	33	32	29	27	26	25

Table 3.4: Outdoor temperature per hour

External wall: 2	Inner wall: 1.8	Roof: 0.3	Windows: 3.5

Table 3.5: U values W/(m^{2}*°C)

Orientation / Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
North	10	10	9	8	7	5	4	3	5	6	7	8	9	10	12	13	15	17	18	19	19	19	18	16
Northwest	12	11	10	8	7	5	3	5	7	14	17	20	22	23	23	24	24	25	25	24	23	22	20	18
East	13	12	9	8	7	5	5	5	7	17	22	27	30	32	33	33	32	32	31	30	28	26	24	22
Southeast	14	12	9	8	6	5	4	7	7	13	17	22	26	29	31	32	32	32	31	30	28	26	24	22
South	15	13	12	9	8	8	4	5	6	6	7	9	12	16	20	24	27	29	29	29	27	26	24	22
Southwest	16	14	9	8	7	5	6	6	7	8	8	8	10	12	16	21	27	32	36	38	38	37	34	31
West	21	19	12	7	6	6	8	8	9	9	9	9	10	11	14	18	24	30	36	40	41	40	38	34
Northwest	18	15	13	11	9	8	8	7	8	7	7	8	9	10	12	14	18	22	27	31	32	32	30	27

Table 3.6: CLTD of the external walls per hour

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	22	17	13	9	6	3	1	5	11	16	22	33	38	43	51	58	62	64	55	45	38	33	26	24

Table 3.7: CLTD of the roof per hour

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	1	0	0	0	0	0	0	2	4	7	9	10	12	13	14	14	13	12	10	8	6	4	3	2

Table 3.8: CLTD of the windows per hour

Orientation / Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
North	0.08	0.07	0.06	0.06	0.07	0.73	0.66	0.65	0.73	0.80	0.86	0.89	0.89	0.86	0.82	0.75	0.78	0.91	0.24	0.18	0.15	0.13	0.11	0.10
Northwest	0.03	0.02	0.02	0.02	0.02	0.56	0.76	0.74	0.58	0.37	0.29	0.27	0.26	0.24	0.22	0.20	0.16	0.13	0.06	0.05	0.04	0.04	0.03	0.03
East	0.03	0.02	0.02	0.02	0.02	0.47	0.72	0.80	0.76	0.62	0.41	0.27	0.24	0.22	0.20	0.17	0.14	0.11	0.06	0.05	0.05	0.04	0.03	0.03
Southeast	0.03	0.03	0.02	0.02	0.02	0.30	0.57	0.74	0.81	0.79	0.68	0.49	0.33	0.28	0.28	0.22	0.18	0.13	0.08	0.07	0.06	0.05	0.04	0.04
South	0.04	0.04	0.03	0.03	0.03	0.09	0.16	0.23	0.38	0.58	0.75	0.83	0.80	0.68	0.50	0.35	0.27	0.19	0.11	0.09	0.08	0.07	0.06	0.05
Southwest	0.05	0.05	0.04	0.04	0.03	0.07	0.11	0.14	0.16	0.19	0.22	0.38	0.59	0.75	0.81	0.81	0.69	0.45	0.16	0.12	0.10	0.09	0.07	0.06
West	0.05	0.05	0.04	0.04	0.03	0.06	0.09	0.11	0.13	0.15	0.16	0.17	0.31	0.53	0.72	0.82	0.81	0.61	0.16	0.16	0.12	0.10	0.07	0.06
Northwest	0.05	0.04	0.04	0.03	0.03	0.07	0.11	0.14	0.17	0.19	0.20	0.21	0.22	0.30	0.52	0.73	0.82	0.69	0.16	0.12	0.10	0.08	0.07	0.06

Table 3.9: CLF of windows per hour

North: 147	Northeast: 565	East: 671	Southeast: 391	South: 140	Southwest: 391	West: 671	Northwest: 565

Table 3.10: MaxSHGF per orientation of the windows

3.7 Configuration files and visualization

All the variables previously presented, and others which are necessary to make the implementation, are defined in **configuration files**. These configuration files enable the specification of the building space, the physical variables of the energy model, as well as the occupant's activity and followed policies.

Both the real-time **visualization**, useful for evaluation, debugging and comprehension, and the appropriate **representation of the results** obtained for their evaluation and analysis are key requisites for a good simulation software. A visualization component is used for analysis and for improving the understanding of energy consumption and occupancy comfort for each strategy.

CHAPTER 4

Architecture

4.1 Introduction

In this section, the implementation of this project, which is named GreenSOBA, is described. The aim of this implementation is to design a system which models the components described in the Chapter 3.

4.2 Overview: GreenSOBA

Firstly, supported in Mesa, a new system of simulation of occupancy based on agents (**SOBA**) has been implemented. This software is useful for conducting studies based on occupancy simulations in buildings, such as drill simulation. It is provided as open source software [27].

Then, its system has been developed to provide a realistic and predicable tool useful for evaluating and managing methodologies for energy building consumption reduction. This work is based on this second and more extended system, named **GreenSOBA** [1], whose complete architecture is represented in Fig. 4.1. The occupants and their behavior, part of the model, the main aspects of the space and the real-time visualization are provided as

SOBA, while the rest of class are the development of GreenSOBA. The model defined in the Chapter 3 is implemented by means of this design, which is described below.

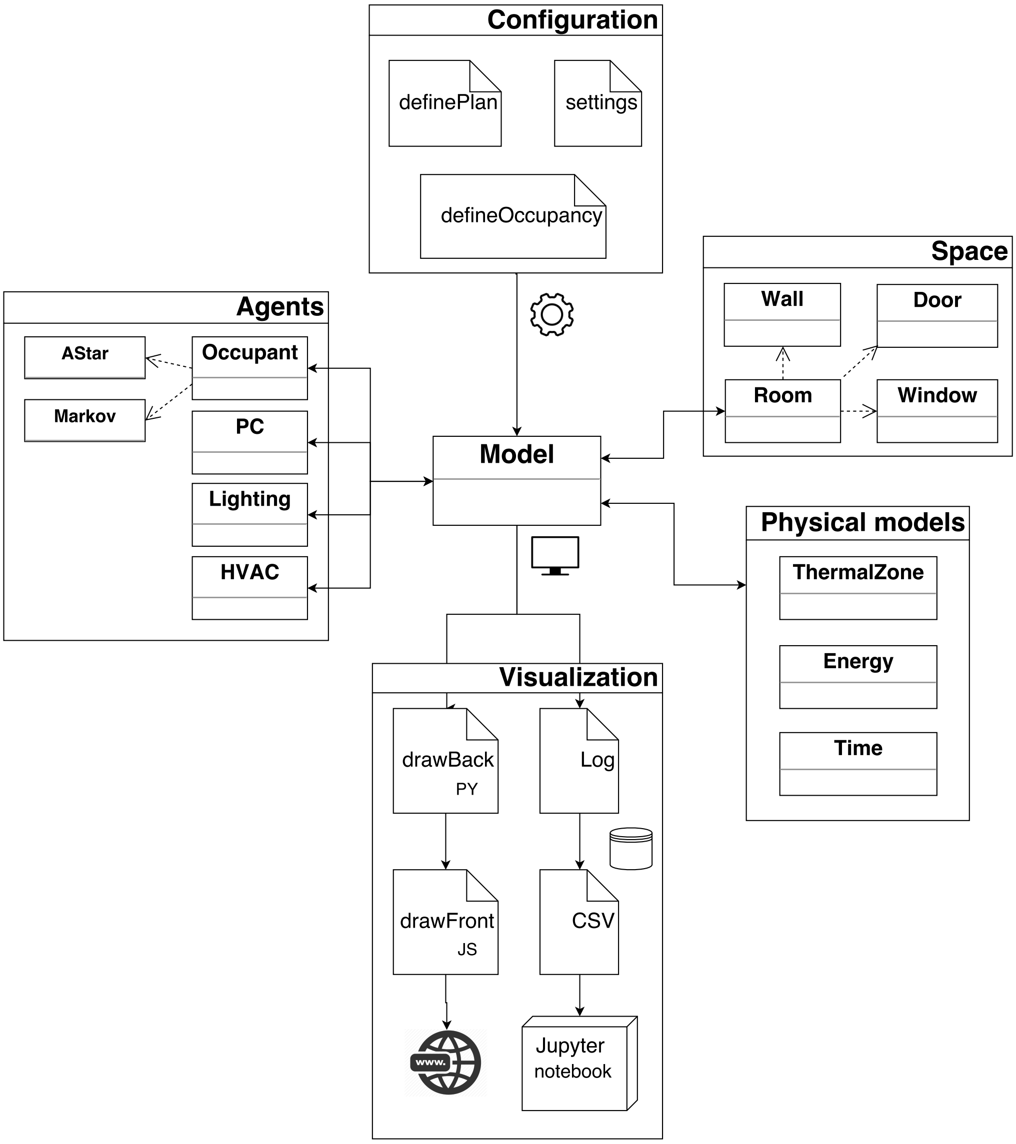

Figure 4.1: GreenSOBA architecture class diagram

4.2.1 Model

The model is the main class of the system. The Model class creates the spaces and the agents and manages all the changes in the model, such as actions and movements of the occupants, in function of the control strategies. In addition, it provides a log with all the measures that enable the evaluation of the simulation.

1. **Initialization**. First of all, in the execution file, the object of the Model class is created. Then, the configuration files are initialized by the Model: *settings*, *defineOccupancy* and *defineMap*. Since GreenSOBA extends MESA, the Model class also creates the scheduler and grid objects. In addition the energy, time and log object are started.

2. **Creation**. Through seven methods, the rooms, the thermal zones and the room components (doors, windows, walls) are created, the plan is defined and the agents are set.

    (a) *createRooms()*. All the information about the rooms and their elements is obtained from the JSON configuration file. For each room, a name, a type, the connections with other rooms, the thermal zone to which it belongs and its measures are given.

    (b) *createDoors()*. Doors are created by defining the rooms with which they are connected.

    (c) *createWalls()*. The windows are set in the proper room with the defined measures.

    (d) *createWindows()*. Both inner and external walls are created with the rooms associated, more than one in the case of the inner walls, and with the corresponding orientation in case of the external walls.

    (e) *setPlan()*. By means of this method the rooms are appropriately and automatically set in the grid by using the connexion between rooms provide in the configuration file.

    (f) *createThermalZones()*. In this method is created each thermal zone, considering than one thermal zone can be corresponded with more than one room, following the information provided in the *defineMap* configuration file. Also in this function is defined the functionality to, if the proactive strategy is run, assign a schedule to the HVAC associated to each thermal zone. It is made by means of obtaining the information about the occupants schedule from the corresponded CSV file generated in a previous simulation and evaluating this information to generate a appropriate and adapted to occupancy schedule for each day.

    (g) *setAgents()*. The lighting system objects are created and associated with each room, in relation one to one. Also the HVAC systems are initiated and associated each one with one thermal zone. The occupants are created following the description defined in the *defineOccupancy* configuration file and the PCs are created and associated with each occupant and with each state in which they are used.

3. **Operation**. During the simulation performance, the model's step is the first to be executed. Depending on the strategy which is simulated, the HVAC system is turned to 'work', which allows the HVAC agent switch itself to the state 'on' if it is required. The variation of temperature model, by thermal loads, is executed. After, the agents' schedule is run.

4. **Control**. The checks and the communication between objects of other classes are defined in the model. Functionalities such as to push an occupant in a room, to obtain occupancy information or to know the state of a door are some examples of the operations of these methods.

5. **Data collection**. After each simulation step, a log entry is created including information about occupant's comfort, energy consumption, from each source, and temporary information used to perform the strategies. Finally, reached the simulation end, the model uses the class log to save the information collected.

4.2.2 Agents

Four agent classes have been defined in GreenSOBA that extend the MESA Agent class. These classes are: occupant agent, lighting agent, equipment agent and HVAC agent. In addition, two classes have been implemented to model occupant's movement and behavior.

1. **Class Occupant**. Each occupant has a type, a temperature of comfort, an environment behavior, one or more personal computers, and a set of states with positions associated to each state.

   When the occupant object is initiated, all the states and the transitions between them, by means of 'triggers', are initialized using the module Transitions. This is, the state machine and the Markov process are defined and created. Each state is given two methods: one that is run when the state is started and another that is run when it is finished. In addition, it is provided a location where they are performed. The same method is used to declare the machine states in the other agents. In this class the following main methods are defined:

   (a) *startActivity()*. This method is run every time that one occupant enters in a new state to obtain a possible movement, by means of an A* search algorithm, and a time of activity to remain in the new state, which is obtained by the model using the *defineOccupancy* configuration file.

(b) *finishActivity()*. This method notifies the model that a state has ended.

(c) *changeSchedule()*. Auxiliary method to check if a time event defined in the occupant's schedule has been reached, evaluating a possible change of state. It is called in each step as evaluation.

(d) *step()*. This method is run in each simulation step to made a change of state, a movement in the building or to advance in a current activity or state. The movement between rooms requires a number of steps, which are obtained with the size of each room and the average speed of movement defined in the *settings* file. The number of steps in each activity is given by the *defineOccupancy* file. The Fig. 4.2 represents this method.

2. **Class Markov**. By means of this auxiliary class, an occupant changes their state, based on a probabilistic Markov chain. For this, the triggers defined in the occupant class are run after an evaluation of the probabilities is made. The value of these probabilities is obtained by the model, using the information given in the *defineOccupancy* file. This class is necessary because of this Markovian functionality is not included in Transition module.

3. **Class AStar**. In this class is implemented the A* search algorithm used by the occupants to move in the building, between rooms, following the optimum way.

4. **Class Lighting**. Each room is associated with an object of this class and vice versa, which are modeled with two states, 'on' and 'off', and parameterized with a consumption and a suitable time to be automatically switched 'off' in the reactive and proactive strategies. In this class, two main methods are defined:

   (a) *sensorCheck()*. With this method, the lighting system is switched 'off' or 'on' in function of the occupancy presence or absent after a suitable time.

   (b) *step()*. This method is run in each simulation step to notice the current state to the model and to run *sensorCheck()* in both strategies reactive and proactive.

5. **Class Equipment**. Each occupant has one or more PC associated. These are modeled with three states, 'on', 'standby', and 'off'. They are parameterized with a consumption, a suitable time to be automatically switched 'standby' and a room. Also, it is given a time to be automatically switched 'standby' from 'on', which is considerably lower than the used in the baseline, and 'off' from 'standby' in reactive and proactive strategies. In this class, two main methods are defined:

(a) *sensorCheck()*. With this method, the pc is switched 'off' or 'standby' in function of the occupancy presence or absent after a suitable time.

(b) *step()*. This method is run in each simulation step to notice the current state to the model, run *sensorCheck()* in both strategy two and three, and to check the automatically switch to standby in strategy one.

6. **Class HVAC**. The heating, ventilation and air conditioning system is modeled with this class. Each thermal zone is associated with one object of this class, which are modeled by means of, firstly, a control variable managed by the model in function of the policies and, then, two states, 'on' and 'off'. The HVAC object has a desired temperature value, a value of comfort medium in the thermal zone, a Fanger's value, a consumption and a heat or cold power, in Watts, which is obtained in the initialization by running the *getMaximunQ()* method belonging to the thermalZone object.

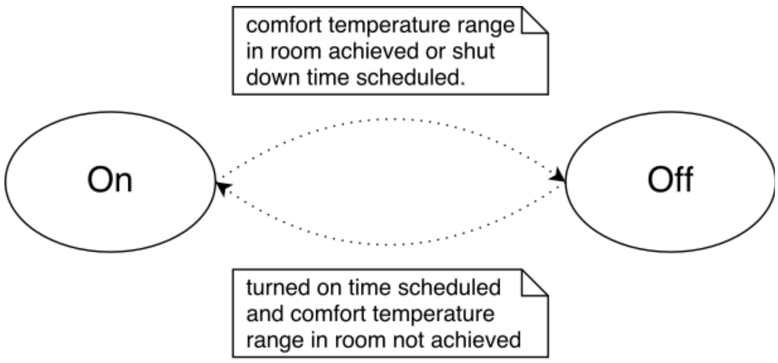

Figure 4.3: HVAC agents' states

In this class, the next main methods are implemented:

(a) *getFangerValue()*. This method follows the modeling described in Sect. 3.5.2 to calculate the Fanger's value associated with the HVAC's thermal zone.

(b) *getComfort()*. Auxiliary method to calculate the value of the comfort of one occupant employing the proposed method, which is described in Sect.3.5.2.

(c) *getTcomfort()*. By means of this method, the HVAC system obtained the ideal temperature, according to the method proposed in Sect.3.5.2, in a thermal zone. For this, an optimization of the proposed function is performed, in order to reduce the number of unsatisfied persons and maximize the average value of satisfied

(d) *step()*. This method is run in each simulation step to, if the model's variable of control 'work' is activated, make the next procedure, which is described in the Fig. 4.4:

i. Notice the state to the model.

ii. If the HVAC object state is 'on', provide a appropriate amount of Joules, as cold in this case, to the thermal zone.

iii. Obtain the both comfort values.

iv. If the strategy is not the Baseline, made the automatic increase of the value of desired temperature, after a suitable time with occupancy absent.

v. If the strategy is the Proactive, obtain the ideal temperature in thermal zone using the occupants' temperature preference.

vi. Switch itself 'on' when the thermal zone temperature is higher than the maximum and 'off' when is lower than the minimum.

4.2.3 Configuration files

The simulation is configured by three different settings files. First, the *defineOccupancy* configuration file enables to modify the occupants' activity and behavior. Second, the *defineMap* file is used to define the building plan. Finally, the *settings* file enables to specify the value of physical variables, such as the building characteristics and some parameters related with the strategies. In the next items are described each of these files with more detail.

1. **defineOccupancy**. This file is divided in two parts.

   First, using a JSON and for each type of occupant, it is given:

   (a) The number of occupants.

   (b) The states, which are defined by means of a name and the room where they occurs. If there is a different position for each occupant, the number of occupants by position should be specified. One example is showed below.

   ```
   {'name':'working in my office', 'position': {'Office1': 2, '
       Office2': 3, ...,'Office14': 2}},
   {'name':'lunch', 'position': 'outBuilding'}
   ```

   (c) In which states the occupants use pc.

   (d) A schedule, which is used together with the Markov operations to model the occupant activity in the building.

   (e) The probabilities of each type of environment behavior.

   (f) The variation and average of the temperature preferences.

After, three methods are implemented:

(a) *returnMatrix()*. By means of this function, the value of each stochastic matrix row is controlled. In this case, it is modified as a function of the time and the agent's schedule. The defined values are different for each type of occupant.

(b) *getTimeInState()*. This method returns the time during which an agent remains in each state before of being able to change to the next. In this case, this value is also modified depending on the time and the agent's schedule, and the values defined changes for each type of occupant.

The daily activity of each type of occupants based on Markovian chains is controlled by these first two methods.

(c) *environmentBehaviour()*. If the strategy reactive is being used, this method is used to control the environment decision, related to switch off or standby the equipment and, with a different configuration, to switch off the lightning system. Decision changes in function of the time, between occupants and among the three types of environmental behaviors.

2. **definePlan**. This file defines rooms and their HVAC system's schedule following a JSON format. For each room, it is given a name, type, thermal zone associated, measures, connections, if they are not declared yet, with other rooms and the windows.

Due to the limitation of the coordinates (x, y) to place rooms with more than four connection to another, it has been chosen to 'split' those real rooms into parts that have four or fewer connections. These partitions are taken as a single room in the simulation by naming the room in this file with a format 'name.id', where 'name' will be common to all. One example is showed below.

```
{'name':'Hall.1', 'type':'hall', 'conectedTo': {'L':'Restroom', 'U':'
    Hall.2', 'D':'outBuilding'}, 'thermalZone':'1', 'measures': {'dx
    ':13, 'dy':5.2, 'dh': 2.98}, 'windows':{'S': {'l1': 1.25, 'l2
    ':2}}},
{'name':'Office1', 'type' : 'office', 'thermalZone':'19', 'measures':
    {'dx':4.57, 'dy':3.64, 'dh': 2.98}, 'windows':{'N': {'l1': 1.25, '
    l2':3.5}}}
```

3. **settings**. Three different aspects are gathered in this configuration file. First, values related with energy, such as the equipment and light consumption. Second, parameters to control the strategies, such as the equipment or HVAC behavior. Third, all the parameters to define the building and climate characteristics employed in the thermal load model.

4.2.4 Space

The modeling of the physical space, the building, has been carried out considering that in a simulation for an energetic research, the model could be simplified to work with occupants who make activities in rooms associated to each activity or state. That is, the coordinates (x, y) or cells provided by MESA are associated with rooms, without entering a higher level of detail. With this assumption, the movement between rooms implies a transition time for each movement corresponding to the sizes of each room and an average speed. According to this, the space implementation is described in Fig. 4.5

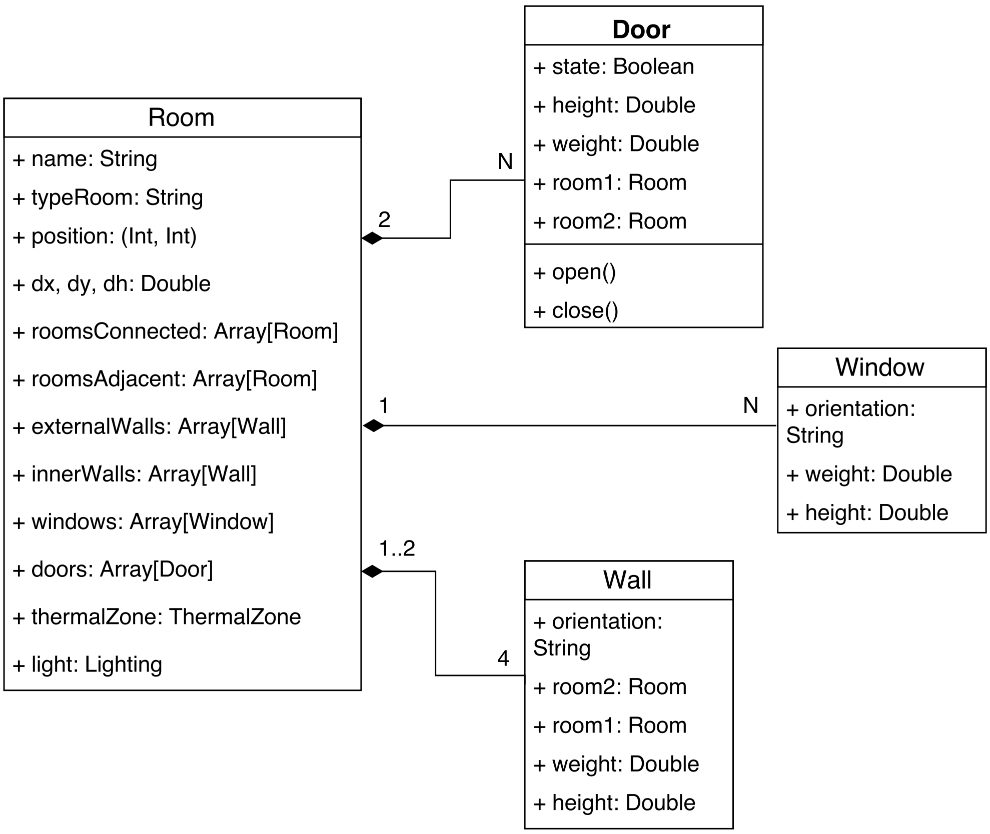

Figure 4.5: Class diagram of the space implementation

4.2.5 Physical models

1. **Class ThermalZone**. All the functionality required to model the Heat Balance Method described in Sect. 3.6 is defined in this class. Each thermal zone object is related to one or more rooms, regulating the temperature in them, and to one HVAC object. One object of this class has a parameter, Q, to store the Julies, gained or lost, due to the thermal loads and other, QHVAC, to make the same with the provided by

the HVAC system. The methods related to this are described below.

(a) *getQ()*. With this method is obtained the value, in Julies, corresponding to the gain or lose thermal load in the thermal zone during a period of time given as parameter. The equations that are described in Sect. 3.6 to model the Heat Balance Method are used in this function.

(b) *getMaximunQ()*. This fuction is run by the HVAC objects to obtain their power, which is a result of employing the method *getQ()* in the worst situation and to multiply this value by a factor (<1) given in the configuration.

(c) *changeTemperature()*. The model calls this method to update the temperature in a thermal zone, by means of applying the equations defined in Sect. 3.6. This process, which is used to model a realistic temperature behavior, is described in the Fig. 4.6.

2. **Class Time**. This timing module is added functioning together with the steps, which is key to achieve a correct performance with facets such as the occupants' behavior, the physical modeling and to collect the energy consumption and comfort value appropriately.

3. **Class Energy**. This class is the used by the model to collect and to classify the energy consumption by step, by day and as total for each source. The values are displayed by means of the result module.

4.2.6 Representation

The real time representation of the simulation performance is provided by MESA. However, the files provided have been extended and adapted to this particular simulation's necessities. One example of the final result is showed in Fig. 4.7. These employed files are the next:

1. **drawBack file**. Two classes are defined in this Python file. The first one is used to render the information about rooms' features, such as the temperature, number of occupants and both comfort measures, to the performance simulation representation. The second one is used to render information about energy consumption, which is display by a real time graph. The two classes' data is provided by the model.

2. **drawFront file**. A JS file to draw the information provided by the drawBack in a explorer by means of a socket.

On the other hand, the visualization of the results after the simulation execution has been implemented by the next files:

1. **Class log**. The model run this class's methods to save the information collected during the simulation. The next methods are provided:
   (a) *collectEnergyValues()*. All the data related to energy collected during the simulation execution is sent to this method, which saves six different CSV files per each strategy.
   (b) *collectComfortValues()*. The comfort values stored during the simulation are save in two different CSV files per strategy.
   (c) *collectScheduleValues()*. The log about the occupants' work schedule is saved with this method.
   (d) *saveOccupantsValues()*, *getOccupantsValue()* and *saveScheduleRooms()*, *getScheduleRooms()*. These methods enable to save temporary information, relevant to model the strategies, during the simulation.
2. **Jupyter Notebook**. By means of this technology, the result graphs are plotted, using the CSV files generated with the log class. The results are showed in Sect. 5.

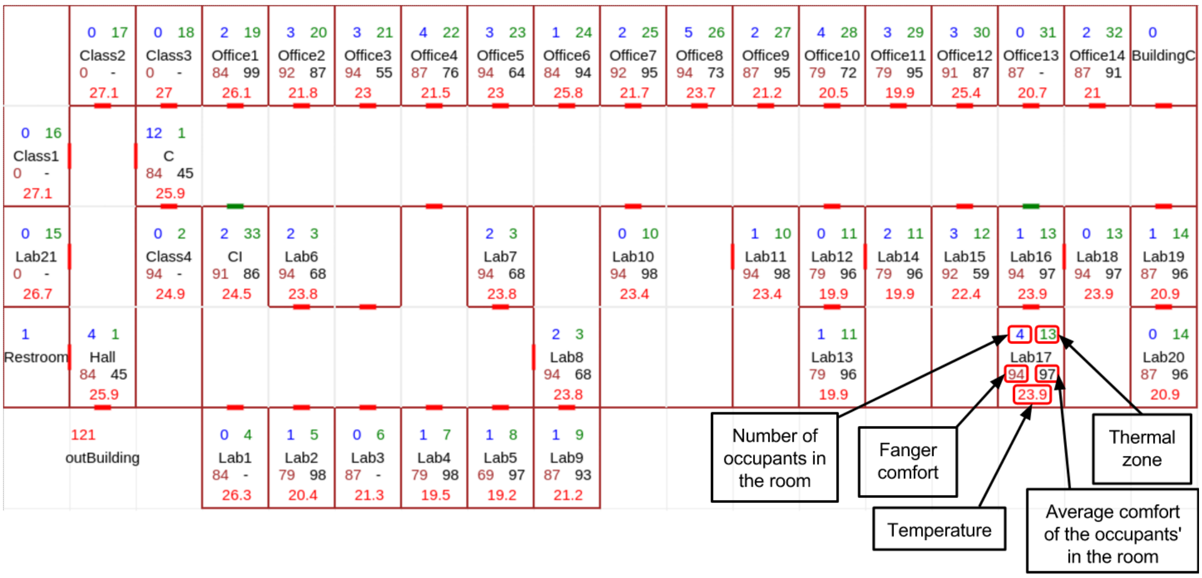

Figure 4.7: Real time representation of the simulation

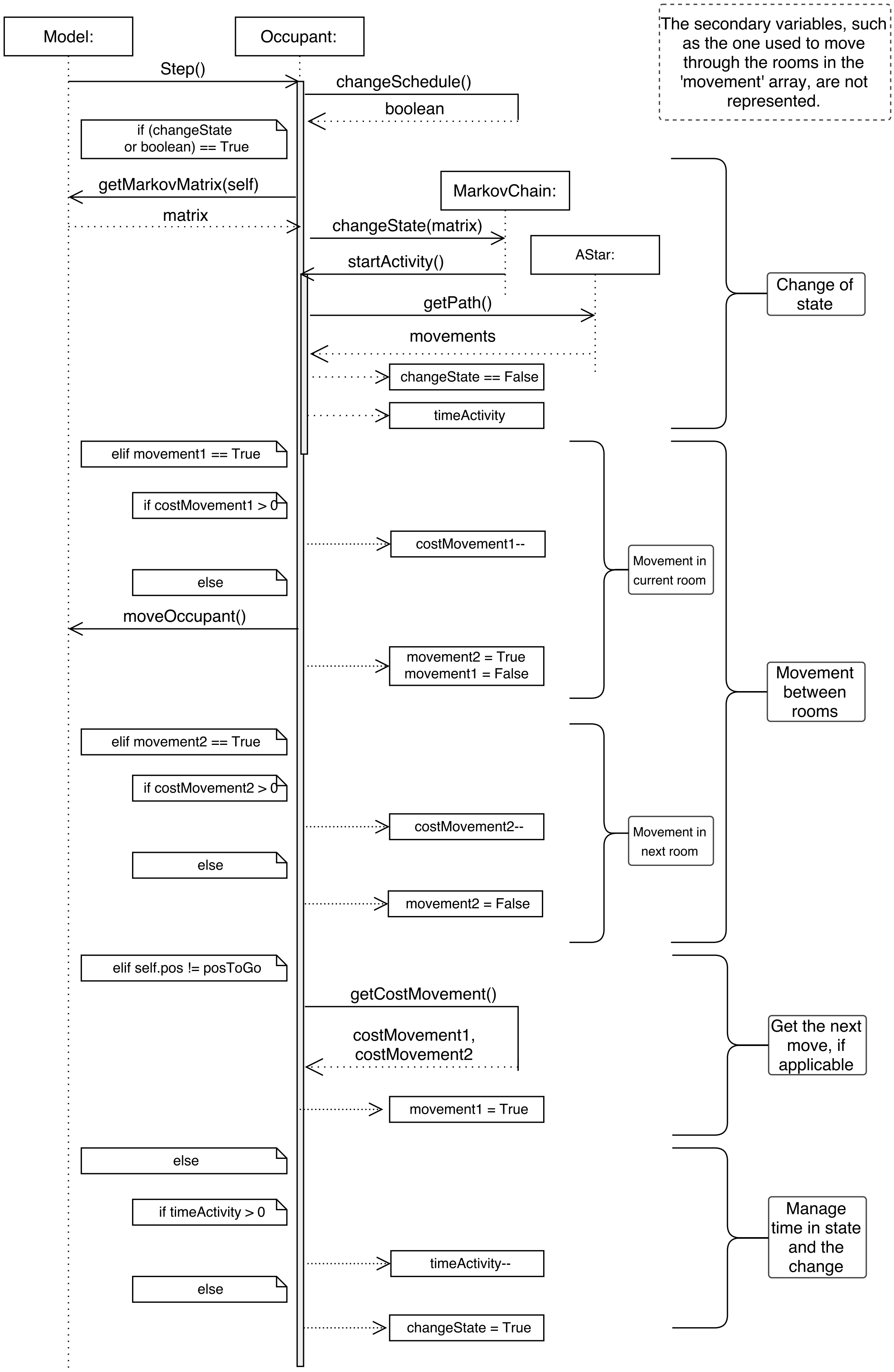

Figure 4.2: Occupants' step method

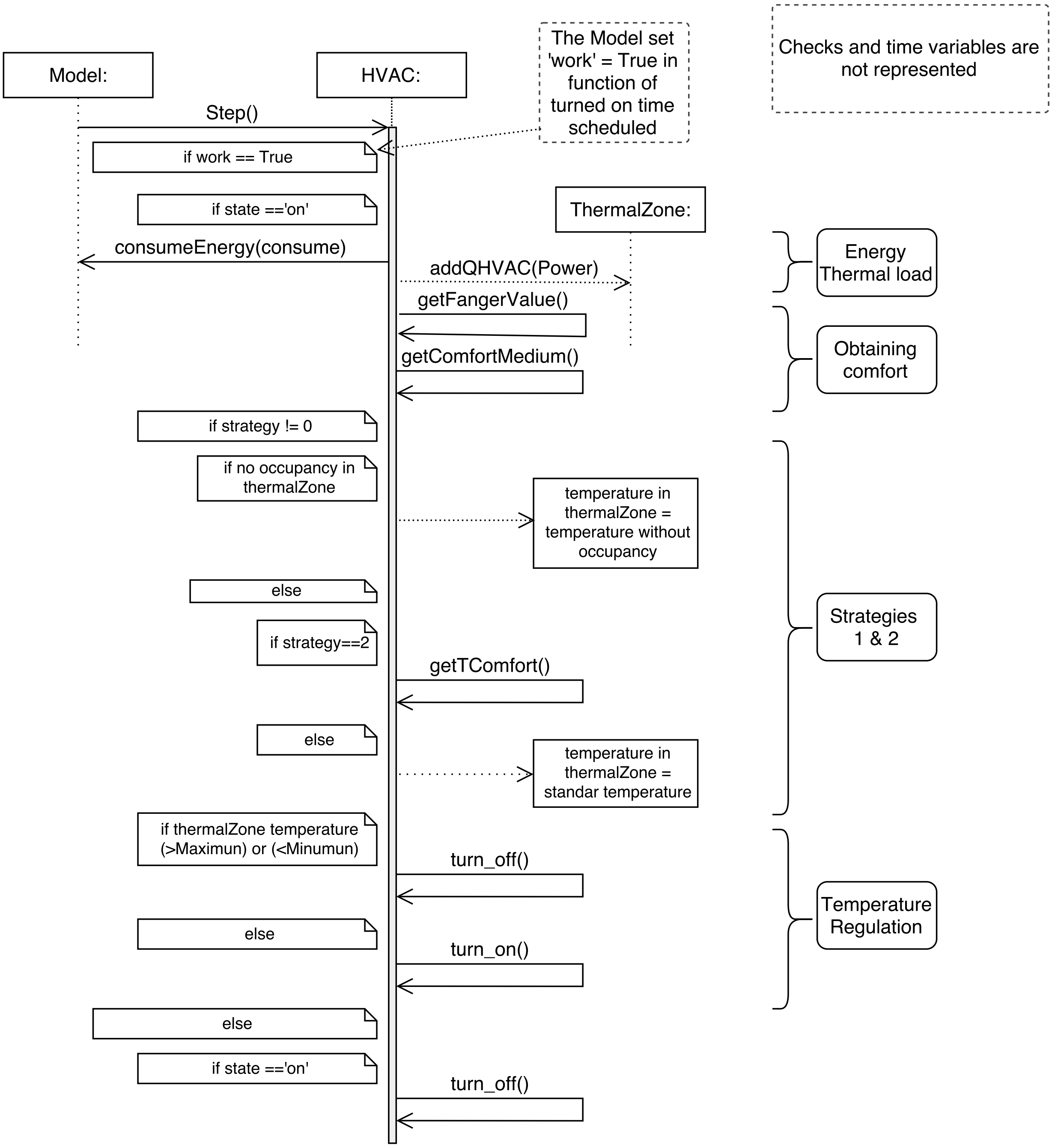

Figure 4.4: HVACs' step method

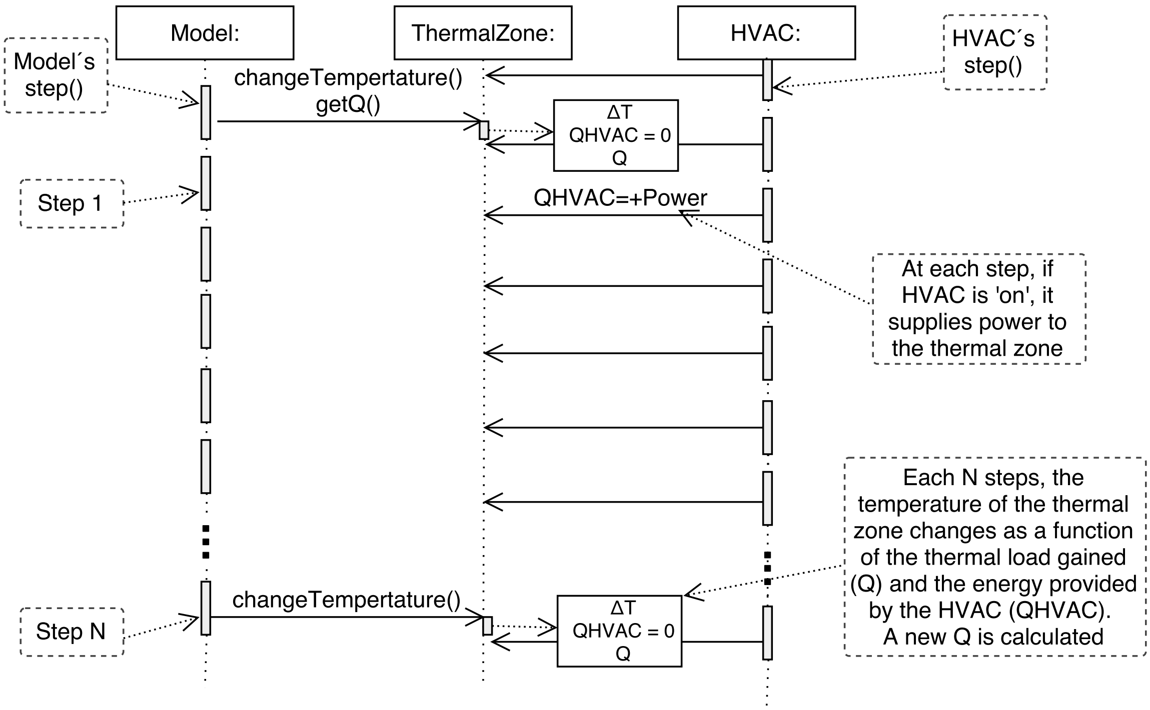

Figure 4.6: Temperature modeling

CHAPTER 5

Results

5.1 Introduction

In this chapter, the results obtained by the simulation of each one of the three strategies are presented, contrasted and evaluated. First, it is described some aspects and considerations about the results to be analyzed. Second, the values obtained about the energy consumption are analyzed and asserted with real information. Finally, the results referents to the comfort are presented and evaluated with respect to energy consumption results.

5.2 Simulation results

The three strategies or policies, Baseline, Reactive and Proactive, which are described in Sect. 3.3, are run one after another, creating log files stored as CSV files to be represented by graphs in a Jupyter notebook. The results generated represent the energy consumption and occupancy satisfaction values during a five labor days period produced by each strategy, enabling to compare and to assess their impact on both variables.

It is indispensable to inform the reader that although the simulation considers students and classes, all displayed results correspond to measures of only the researchers and professor occupants' actions. That is because although a detailed simulation of the university building requires modeling classes, students and professors giving classes, the policies to reduce energy consumption and to improve the occupancy comfort are barely interesting when the schedules are so regular and the occupants' actions so limited as students attending two hours at class.

Besides energy and comfort results, the occupants' activity by hours in the building is registered to support the results understanding and evaluation. In the Fig. 5.1 is displayed the number of occupants who are working in their workplace, having a meeting o giving classes in the building floor studied, in function of the hours.

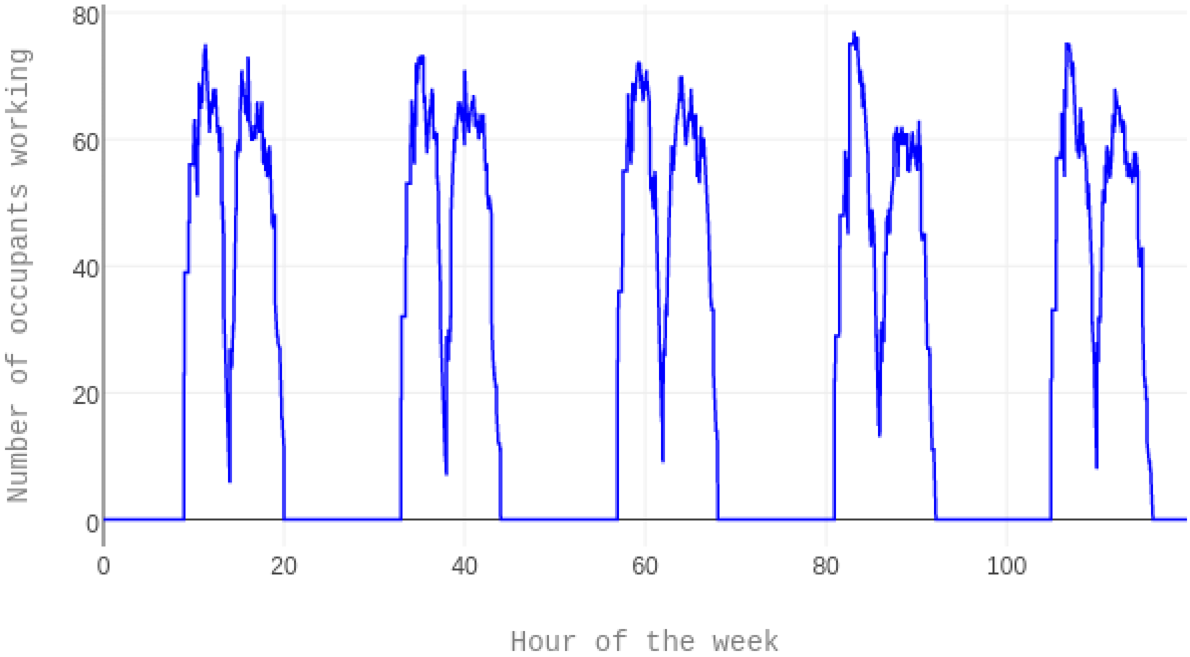

Figure 5.1: Occupancy activity

As can be seen, in this graph is represented the daily activity by means of the arrivals, leavings and lunch times, together with the activities which are made during the work time, such as take a resting, modeling the behavior described in the Sect. 3.5.1. The displayed schedule can be compared with the energy and comfort results to assess the obtained values.

5.2.1 Energy results

All the displayed results are measured in Watts or Watts hour and represent the energy consumption associated with the HVAC systems, the personal equipment and the lighting system used by 80 people.

In Fig. 5.2 is showed the total energy consumption of the three strategies with respect the time during one labor day.

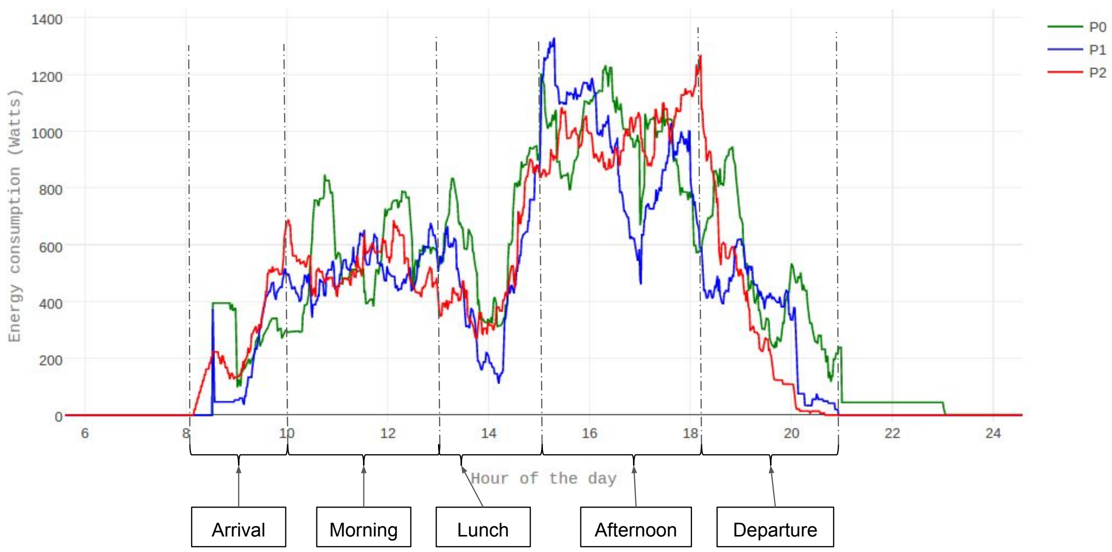

Figure 5.2: Total energy consumption of the three strategies during one day

In the below graphs, we present the total energy consumption with respect to time during five labor days. In Fig. 5.3, the comparison between the Baseline and the Reactive strategies is showed. In Fig. 5.4, the Baseline and the Reactive strategies are compared. Finally, in Fig. 5.5, the comparison between Reactive and Proactive strategies is showed.

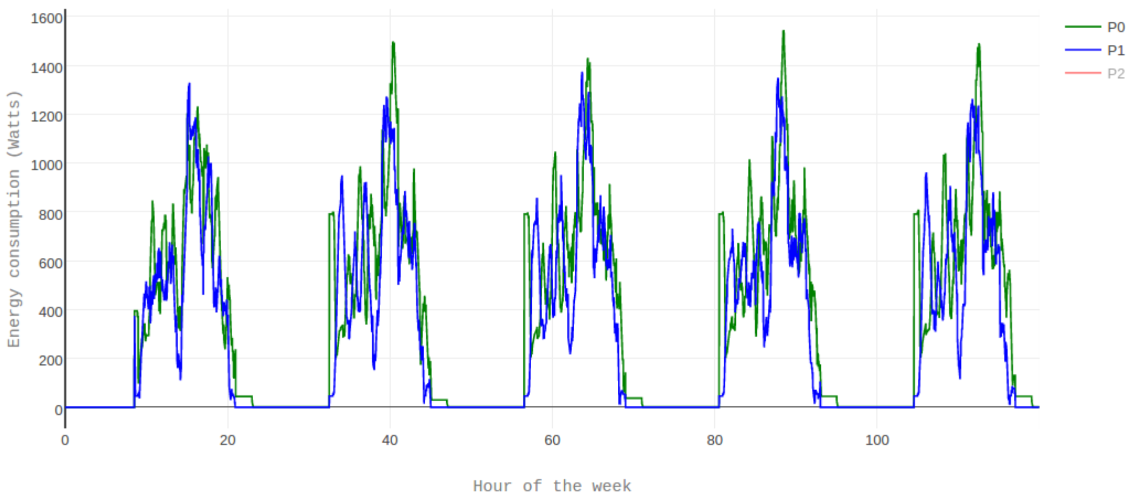

Figure 5.3: Energy consumption comparison between Baseline and Reactive

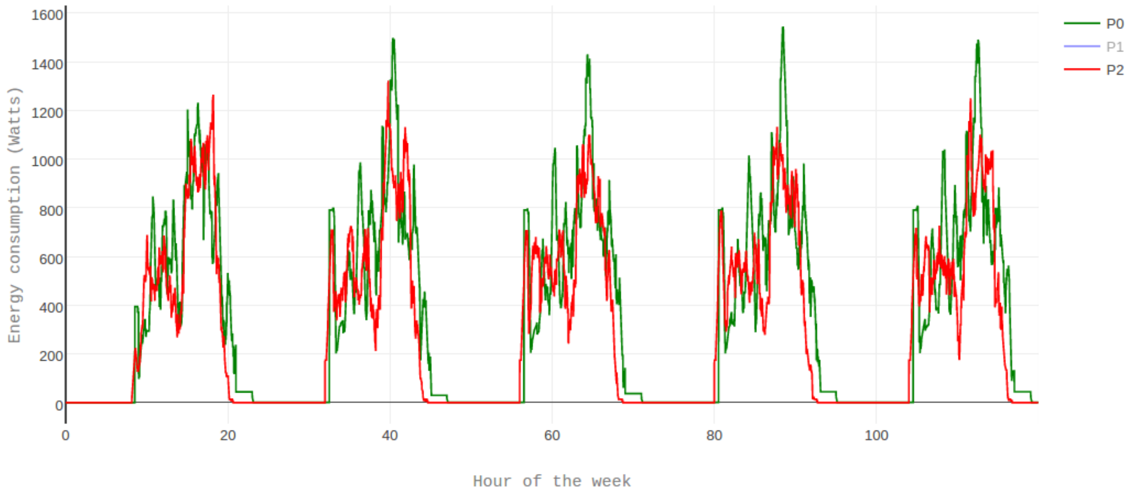

Figure 5.4: Energy consumption comparison between Baseline and Proactive

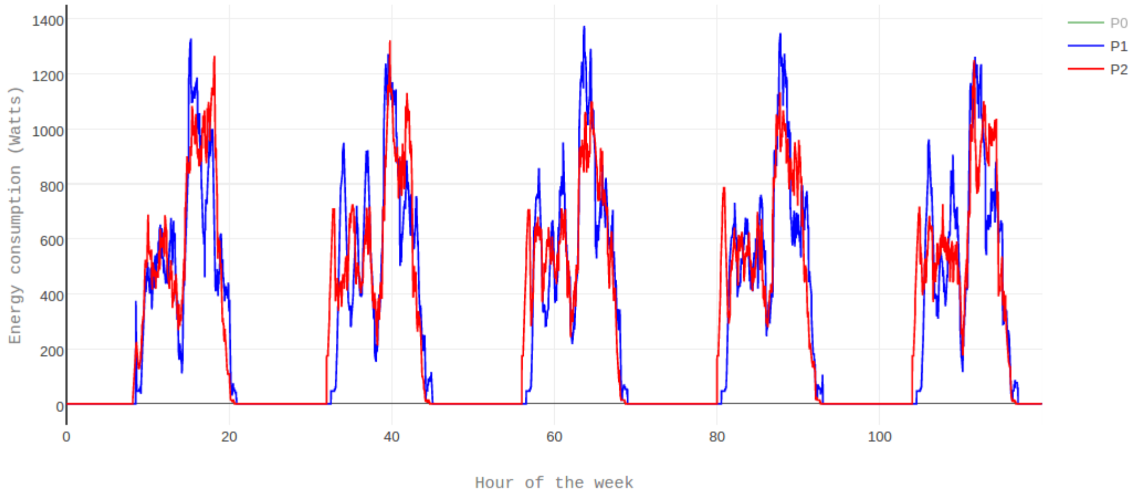

Figure 5.5: Energy consumption comparison between Reactive and Proactive

After analyzing the energy consumption following the different policies in the above graphs, we obtain the following conclusions. First, all the graphics present five defined areas, independently of the used policy. These phases correspond to i) arrivals, where there is a growing consumption; ii) the morning (between arrival and lunch), where the consumption is medium; iii) lunch time, when the consumption decrease; iv) afternoon (between lunch and departure), where the temperatures are higher, so the consumption is also higher; and v) departure, where there is a step representation. These areas are represented in Fig. 5.2. This seems reasonable. Each of these areas is modified by both strategies in contrast with the Baseline one.

A comparison between Baseline (P0) and Reactive (P1) strategies is made in Fig. 5.3, where a greater number of peaks, and with a larger depth (less consumption), is displayed by the P1, because of the ability to react to the occupants' actions. It is especially clear during the lunch and end of work time, where the equipment and the HVAC system take an appropriate situation of the least consumption independently of the occupants' environmental behavior. Besides, relating to the reactive functionality, although in P1 the time in which the HVAC is started is the same, controlled by the fixed schedule, until there is some occupant in the room the reached temperature by the HVAC is higher than the fixed in the P0.

Observing the Reactive (P1) and Proactive (P2) comparison in Fig. 5.5, an evaluation between both strategies is made. As expected, because the proactive policy includes the reactive one, the peaks number and their depth are similar, which can be more clearly seen in Fig. 5.4. However, with the proactive strategy is obtained an extra variation with random behavior produced by the temperature voting method, and a function shape more adjusted to the occupants' schedules, because of the learning ability of these which enables to anticipate to arrivals and leavings.

In the below graphs, we present the energy consumption with respect to each day of the week. In Fig. 5.6, the daily energy consumption or equipment and lighting system is showed. In Fig. 5.7, the daily consumption of the HVAC system is presented. In Fig. 5.8, the total daily energy consumption is showed.

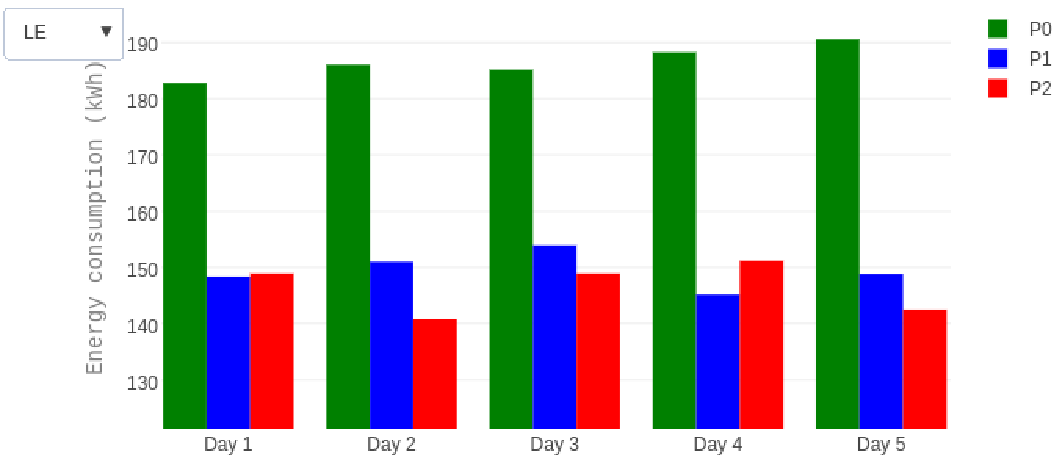

Figure 5.6: Daily energy consumption of Equipment and Lighting system

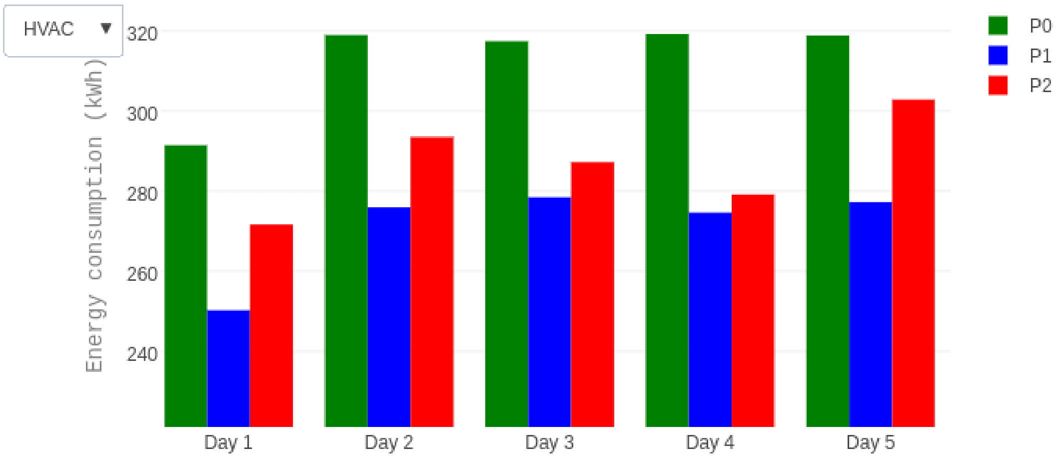

Figure 5.7: Daily energy consumption of HVAC system

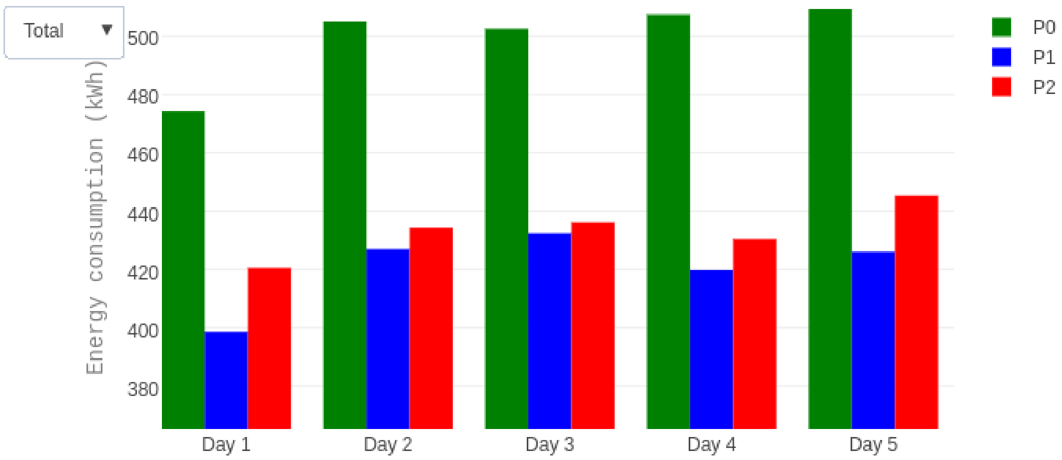

Figure 5.8: Total daily energy consumption

Finally, we present the energy consumption corresponding to all simulation, five labor days.

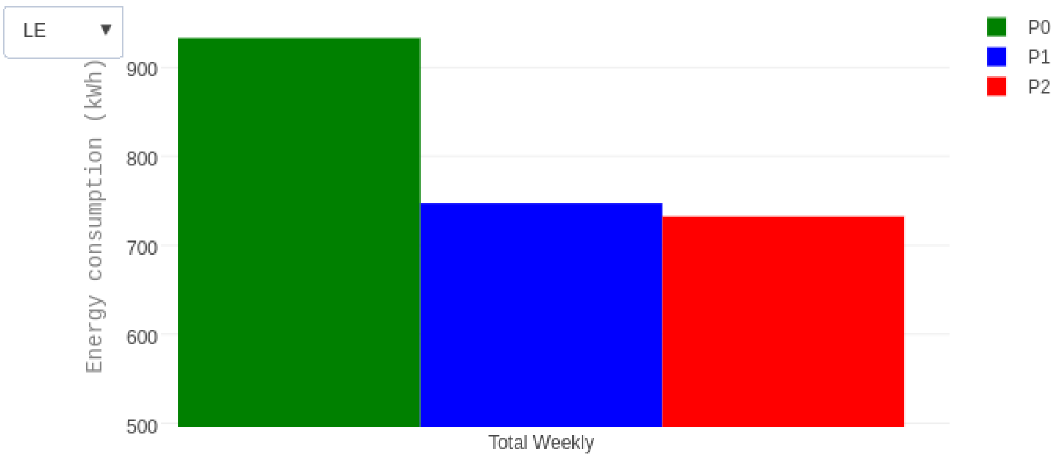

Figure 5.9: Weekly energy consumption of Equipment and Lighting system

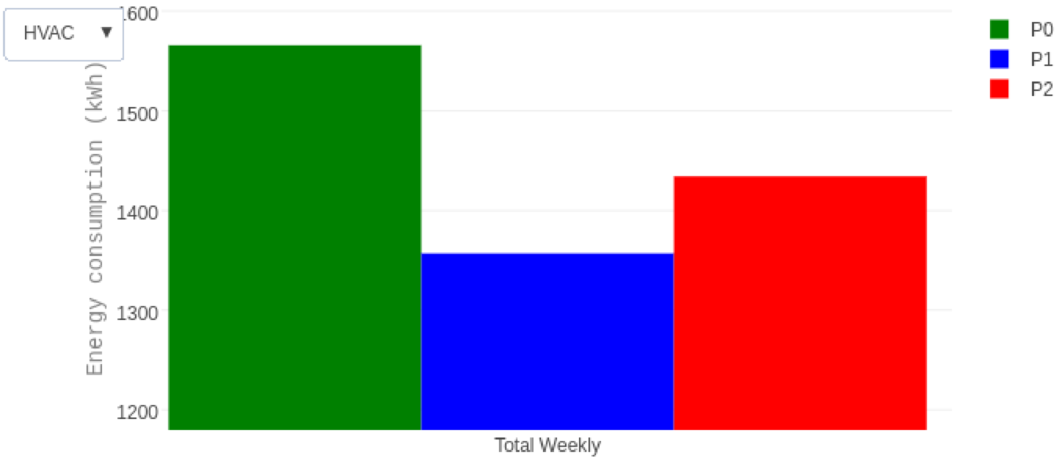

Figure 5.10: Weekly energy consumption of HVAC system

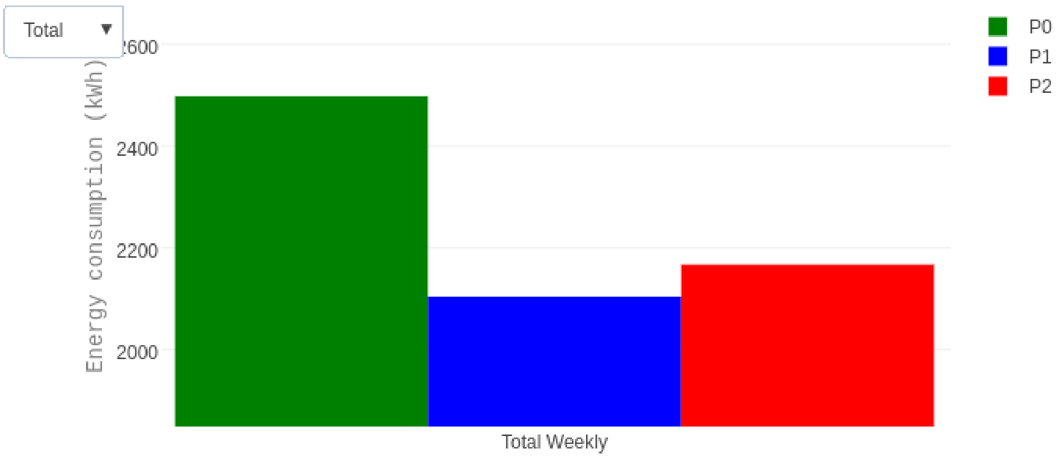

Figure 5.11: Total Weekly energy consumption

According to above graphs, an energy saving is achieved with both strategies in comparison with the Baseline policy, which can be clearly visualized in Fig. 5.11, where the total energy consumption of all week is displayed. A 15.79% energy saving is achieved employing the Reactive strategy comparing with the Baseline, and a 13.28% employing the Proactive one. As we can see in Fig. 5.9, the percentage of energy reduction generated by the equipment and lighting system, around a 20%, is similar for both Reactive and Proactive strategies.

However, in Fig. 5.10 it is shown how, the HVAC consumption associated to Proactive policy is higher, due to the temperature preferences and the adaptation to the occupancy schedule, providing a better temperature in the room. A value of 14.34% with the Reactive strategy and a 8.38% with the Proactive one are achieved.

5.2.2 Comfort results

The value of occupants' comfort obtained with each strategy is evaluated with both methods described in Sect. 3.5.2: the standard Fanger's method and the one proposed in this project, which, as can be seen below, provides interesting results.

In first place, the comparison between the comfort obtained by the policies is made with the Fanger method.

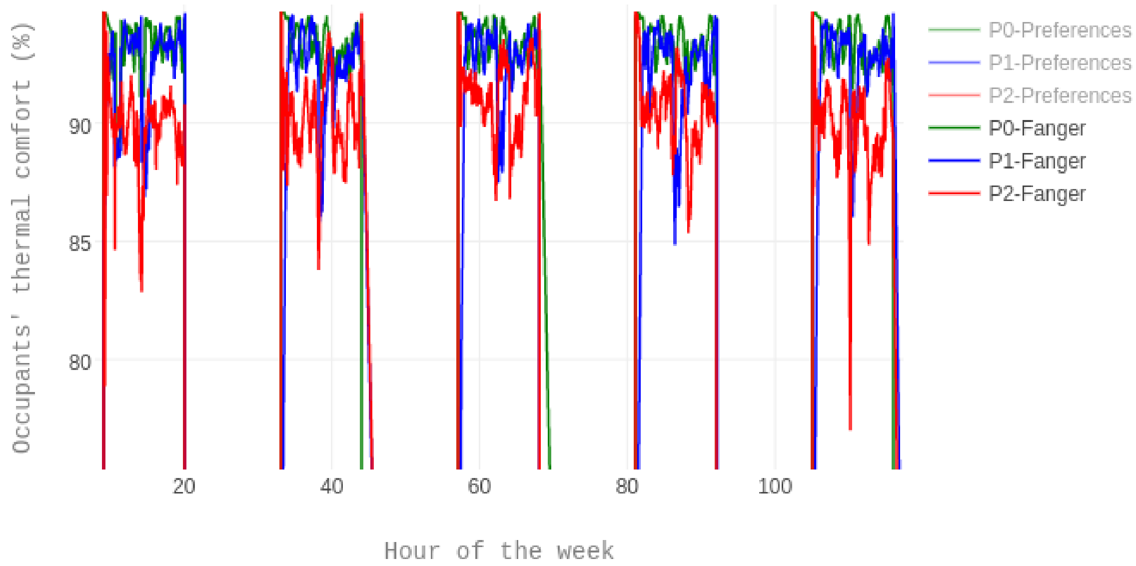

Figure 5.12: Comfort values obtained by the Fanger's method

The Baseline (P0) and Reactive (P1) comfort results are showed in Fig. 5.12, where it can be observed that the comfort value for Reactive strategy is mainly inferior due to the reactive behavior, allowing higher temperatures when there is not anyone in the room, appreciable effect principally in arrivals and during lunch time.

In the same figure, the Proactive (P2) policy is also displayed and, in this case, the comfort results obtained by this strategy are even worse than the obtained by the Reactive one. That is, the temperature in the rooms is frequently more different than the standard, which is used by the Fanger's method as the optimal value.

In second place, the analysis is made using the proposed method, which performs the comfort evaluation by means of the occupants' temperature preference directly, information which is not considered by the previous method.

The Baseline (P0) and Reactive (P1) comfort results are again compared in Fig. 5.13.

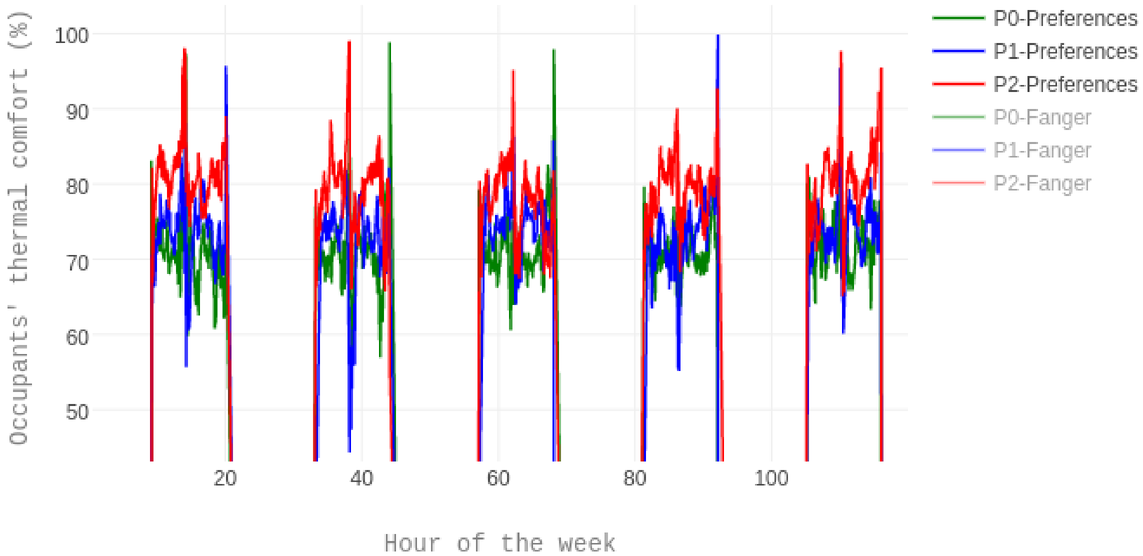

Figure 5.13: Comfort values obtained by the proposed method

The values obtained by this method are more variated, with more peaks and scaled in a different way, but provide a conclusion similar to the acquired in the Fanger's method.

However, an interesting result is achieved from the same graph if it is contrasted the occupants' comfort obtained by the Baseline (P0) with the Proactive (P2) strategy. In the previous analysis based on Fanger's method is concluded that the Proactive strategy provides considerable worse results than the Baseline in temperature conditioning. However, as is displayed in this second graph, when the different occupants' preferences are considered, the Proactive strategy obtains the best occupants' comfort results, around an average of 11% more than the Baseline, because of the ability to know the occupants' temperature preferences, which are usually different than the standard value.

5.2.3 Result summary

A **summary** of all obtained results are described in Table 5.1.

	Energy comsuption (kWh)			*Energy saving with respect to Baseline*			*Average Value of comfort*		*Comfort improvement*	
Strategy	*HVAC*	*Equipment & Lighting*	*Total*	*HVAC*	*Equipment & Lighting*	*Total*	*Fanger's Method*	*Preferences Method*	*Fanger's Method*	*Preferences Method*
Baseline	1565.6	932.8	2498.5	-	-	-	94.08%	71.84%	-	-
Reactive	1356.7	747.2	2103.9	14.34%	19.89%	**15.79%**	93.45%	71.58%	-0.63%	**-0.26%**
Proactive	1434.4	732.2	2166.7	8.38%	21.5%	**13.28%**	89.86%	82.87%	-4.22%	**11.03%**

Table 5.1: Result summary

5.2.4 Simulation Evaluation

A monitoring system is installed in the real building, which is modeled in this work. This control system is a project carried out by an university department, the ITD (Innovation and Technology for Development) of the Universidad Politécnica de Madrid [18]. The results of monitoring the daily energy consumption of the modeled building are shown in Fig. 5.14, in which a constant consumption can be seen due to systems connected permanently, such as servers and databases centers, and a variable consumption due to human activity. This deduction is achieved by comparing a working day with a weekend day.

The consumption of a working day is 4433.82kWh, while that in a weekend day is 2820.32kWh. That is a consumption of 1613kWh in the whole building and a total energy consumption of 403.375kWh in one of its four floors.

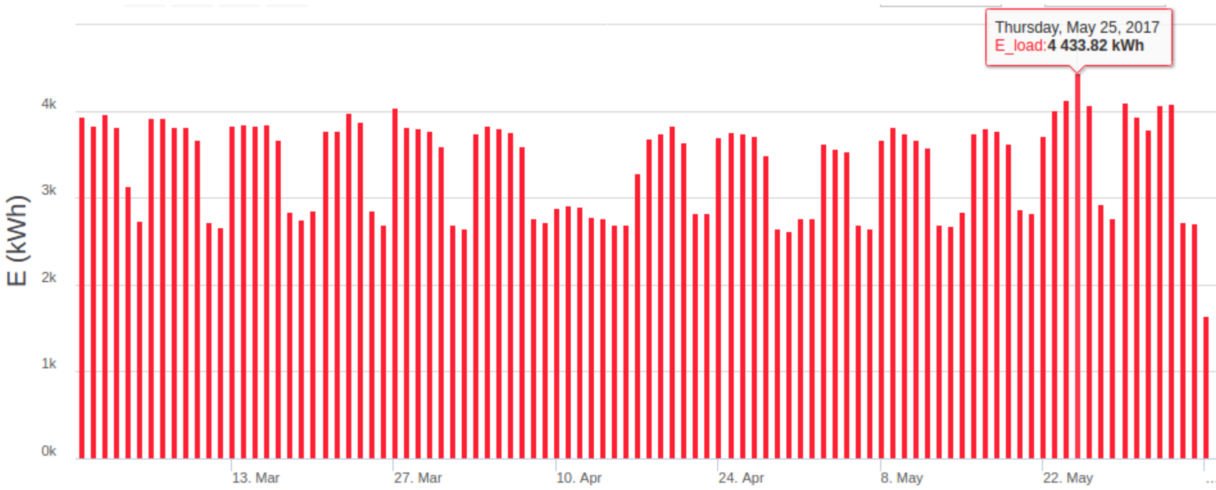

Figure 5.14: Real monitored energy consumption in the modeled building [18]

Comparing this result with which is obtained by the simulation, 2498.5kWh in one week and a average value of 499.7kWh, there is a small variation, which is due to the fact that the month in which the real value is measured is May and the simulation is performed in a month with worse thermal conditions. However, an important point of credibility on the simulated model can be affirmed.

CHAPTER 6

Conclusions and future work

6.1 Conclusions

This project has designed, implemented and evaluated a MAS simulation system for improving the efficiency consumption and occupancy comfort in a university building. For this purpose, three control strategies have been evaluated, Baseline, Reactive and Proactive, by means of simulations configured with data from reality, obtained from a survey, about real occupants' schedule, temperature preferences and environmental behaviors; and performed with a multi-agent system and electrical and thermal physical models. Motivating results to continue defining and evaluating different strategies to employ new technologies in the building management system have been obtained.

An 15.79% energy saving have been achieved by the comparison between the Baseline control strategy and the Reactive one, but the occupants' comfort has been reduced in around 0.26%. The best results have been achieved with the Proactive strategy, which has provided a 13.28% energy saving and a 11% the occupants' comfort improvement in the building. According to that, the energy efficiency provided by the employment of accuracy presence sensors and the huge advantage of using a voting method to improve the occupants´ comfort and energy saving are the strongest conclusions.

It should be noted that employing the model and evaluation methods presented, better results could be obtained if (a) an average situation was considered instead of a unfavorable one and (b) the number of occupants in the building was smaller.

Besides, an open source simulation software of occupancy in buildings based on Multi-agent system is described in this article, which can be useful to make research related to crowds in buildings by means of agents, space and model re-configuration, so enabling to model different buildings, technological elements and human activities and behavior to evaluate approaches, being already provided a tool based on thermodynamical and electrical models.

6.2 Future work

In accordance with the technology evolution, new strategies for providing energy saving and added values for the occupants in buildings will be evaluated. New interaction ways between human and centralized manage systems, providing distinct and innovative models to configure and control the environment, will be designed. It is important to highlight that some of these strategies which should be approached not only the operation made by the building management system but also the methods by means of which the occupants can obtain relevant information and take decision on their actions accordingly, operating the intelligent devices as informative and educational tools which enable to achieve energy saving together with better performance. Relating to new intelligent and interactive technological devices, it will be necessary to design and to experiment with different methods to resolve diverse problems or conflicts that could appear in relating to achieve agreements on technological configurations, for instance, varied voting methods to determinate the temperature in a room. Besides the approach focused on the occupancy, other building manage policies based on automatized control of different influential elements in energy and comfort, such as the automatic windows´ opening and closing in function of the sunbeams and outside temperature or regulation of light intensity will be meditated.

In relation to the simulation software, improvements which enabling more accurate occupants' behavior definition will be implemented. Related with that, acquire and employ real devices which enable contrast, evaluate and enhance the occupancy modeling performance in the simulation with from reality data is also an interesting future work.

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