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AN ORGANIZATION BASED MULTI AGENT SYSTEM FOR SMARTHOME MANAGEMENT

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"Os obstáculos são aquelas coisas terríveis que você vê quando desvia os olhos do seu objetivo."
(Henry Ford)

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UMA ORGANIZAÇÃO BASEADA EM SISTEMA MULTI AGENTES PARA GERENCIAR UMA *SMARTHOME*

RESUMO

Buscando enfrentar os desafios de gerar energia de forma mais limpa, novas técnicas precisam ser desenvolvidas tanto para a produção de eletricidade com baixa emissão de gás carbônico quanto otimizar a distribuição e consumo de energia existente. Técnicas foram desenvolvidos especificamente para combater este último desafio. Nossa pesquisa tem como objetivo contribuir para melhorar a eficiência do uso de energia em uma residência modelando os eletrodomésticos como um sistema multi agentes (MAS). Modelamos este sistema como uma organização virtual em que os agentes formam grupos e hierarquias e seguem específicas regras de comportamento. Este modelo visa minimizar o consumo de energia, enquanto alcança um equilíbrio entre o conforto do usuário e o custo da energia, além de limitar picos de demanda de energia.

Palavras-Chave: Gerenciamento do lado da demanda, Smart Grid, Smart Home, programação orientada a agentes, JaCaMo.

AN ORGANIZATION BASED MULTI AGENT SYSTEM FOR SMARTHOME MANAGEMENT

ABSTRACT

In order to address the challenges of greener energy generation, new techniques need to be developed both to generate electricity with lower emissions and to optimize energy distribution and consumption. Smart grid techniques have been developed specifically to tackle this latter challenge. Our research aims to contribute to improve the efficiency of energy use within a single household by modeling appliances as a multi agent system (MAS). We model this system as a virtual organization in which agents form groups and hierarchies and follow specific behavioral rules. This model seeks to minimize energy consumption while reaching a tradeoff between user comfort, energy cost and limiting peak energy usage.

Keywords: Demand Side-Management, Smart Grid, Smart Home, Agent Oriented Programming, JaCaMo.

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1. INTRODUTION

Electricity is the most versatile and widely used form of energy, as such, global demand is growing continuously. However, electricity generation is currently the largest single source of greenhouse gas emissions, making a significant contribution to climate change. To mitigate the consequences of climate change, the current electrical system needs to undergo adjustments. The solution to these problems is not only to generate electricity more cleanly, but also to optimize the use of the available generating capacity. To achieve such optimization, the *Smart Grid* comes into play.

A *smart grid* is an electrical grid that uses information and communications technology to gather and act on information. The smart grid can take action on the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity [30]. The term smart grid has come to describe a next-generation electrical power system that is typified by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy. Smart grid initiatives can provide more electricity to meet rising demand and quality of power supplies, integrating low carbon energy sources into power networks. It is capable to respond intelligently to changes in demand to help balance electrical consumption with supply, as well as the potential to integrate new technologies to enable energy storage devices and the large-scale use of electric vehicles.

Demand for electricity should be made more adaptive to supply conditions, avoiding peaks of demand, resulting in a more efficient grid with lower prices for consumers. As a result, the new electrical grid intends to achieve an economic balance and increase the efficiency of the current the electrical supply. Energy efficient technologies such as intelligent controls systems adjusting the heating temperature and the illumination can help the management of consumption in buildings and houses. Such intelligent control system can give consumers control over the amount of electricity they use. Furthermore, the intelligent control system can integrated into the power grid through equipment capable of collecting data about electricity consumption and of communicating with others entities in the power grid. A key element that allows all of the emerging smart grid technologies to function together is the interactive relationship between the grid operators, utilities, and the user. Controls in the household and appliances can be set up to respond to signals from the energy grid to minimize the energy use at times when the power grid is under stress from high demand, or even to shift some of their power use to times when power is available at a lower cost. This intelligent control system inside a household introduce the concept of *Smart Home*.

Within the smart grid, a smart home is a household that has highly advanced automatic systems responsible for manager and control the smart appliances. Our main contribution is an agent-based smart home model whereby individual autonomous agents are deployed to control each household energy consuming device, as well as an agent coordinating them all through the energy meter. This model should allow a smart home to become more collaborative with the electric grid by balancing energy demand, increasing the resilience of the household as well as optimizing user comfort. During the development of this work we produced a paper with partial results that was accepted and presented in workshop on collaborative online organizations (COOS'13) at 12th international conference on autonomous agents and multi agents systems (AAMAS 2013) [29]. After that we were invited to extend our paper to submit to the journal of advanced computational intelligence and intelligent informatics (JACIII). The Appendix A shows this paper.

The following sections will present the research question, the objectives proposed in the plan of study and research, the methodology that guided the development of this dissertation and after all how this document is organized.

1.1 Research Question and Objective

Smart grid initiatives seek to increase the efficiency of the electric grid. There are many different kinds of entities present in the electrical grid that result in different demand profiles, the electrical grid must become more adaptive for this heterogeneous demand. To attend this heterogeneous demand it is necessary a control system that can communicates with the electrical grid entities, controlling peak of demand and maximizing electricity usage.

Once the control system communicates with each household through the Smart Meter it is possible to know the household energy profile. This knowledge can help the management of the electrical grid. In this context, we proposed the following research question:

"How to discover the entities on the grid and get them to communicate with each other in order to increase control of the power grid, reducing the occurrence of peak demand and assisting users to better manage their households by optimizing energy usage?"

To address this research question we formulated the following hypothesis:

It is possible to strike a balance in optimizing comfort, electrical efficiency and increasing the resilience of a household, by modeling the appliances and the elements of the grid as a multi agent system. In this system, the appliances, the meter and the elements of the generation system are modeled as agents that work to improve the collaboration of the household with the grid.

Our main objective is to develop a Smart Home model embedding individual agents deployed in each household entity. The model presented in this document allows the Smart Home to become more collaborative with the electric grid by balancing energy demand, increasing the resilience of the household as well as optimizing users well-being.

1.2 Methodology and Text Organization

This document is organized in four parts. The first part was the *study*, where we analyzed the different types os appliances, studied the different types of micro generation and investigated the Brazilian household users. Chapter 2 reviews the background required for our definition of a smart home model and Chapter 3 introduces the user profile in Brazil.

The second part focuses on the *design* of the smart home model, as well as the different users profiles, e.g., users that do not care about the electric cost and prioritize their comfort and users that prefer to give up comfort to save money in the electric bill. Chapter 4 introduces the Smart Home model itself, the appliances description and the organization model.

The third part is the *development*, where the household control system and the communication protocol between smart entities were developed. Chapter 5 introduces the control system and the communication protocol.

In the last part we *validated* the model, run simulations crossing different set of appliances, different set of micro generation system, different users and household configurations profiles. Finally the results were analyzed. Chapter 6 shows how we evaluated the model proposed. Finally Chapter 7 concludes this dissertation and proposes future works.

In Figure 1.2, we can see the Research Design, an illustration of the phases for this research, this design was a flow guiding the phases of Study, Design, Development and Validation. These four phases were necessary to the research accomplishment.

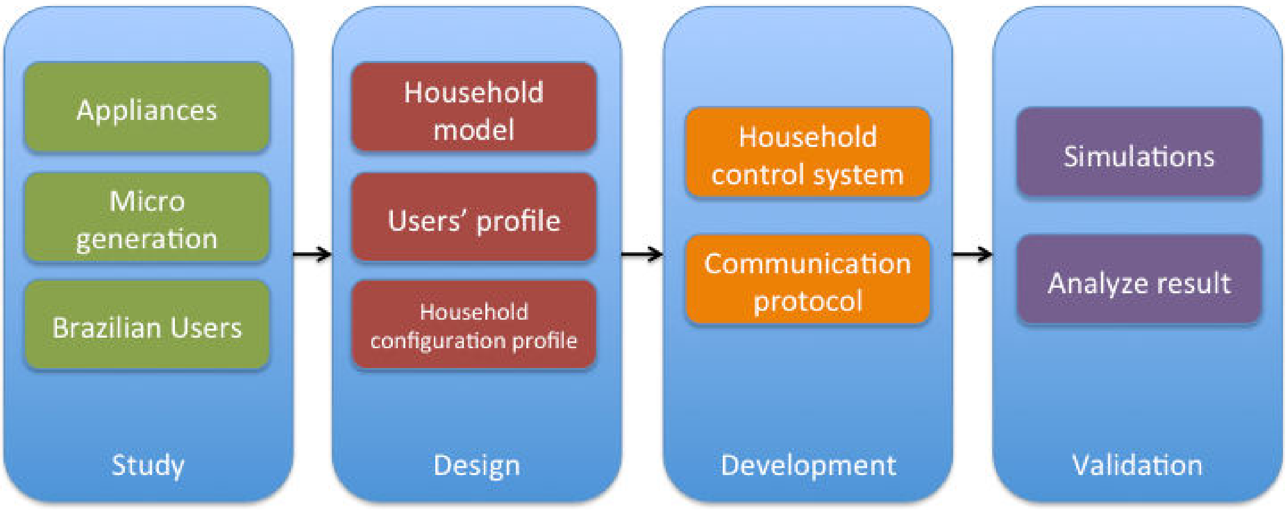

Figure 1.1 – Methodology

2. BACKGROUND

This chapter presents how the electric power industry generates, transmits and delivers energy; the concept of smart grid, its characteristics and the key components of the smart grid — demand-side management, electric vehicles, virtual power plants, the emergence of prosumers, and self-healing networks. Moreover, this chapter also introduces the concepts of microgrid smart home in the power industry. After that we introduce the agent oriented programming through DBI architecture, the agent speak language and the JaCaMo framework

2.1 Electric Power Industry

The power industry is divided into three major sectors: generation, transmission and distribution.

Electricity *generation* is the large-scale process of generating electric power for industrial, residential, and rural use, generally in stationary plants designed for that purpose. Steam turbine generators, gas turbine generators, diesel engine generators, alternate energy systems (with the exception of photovoltaic power cells), even nuclear power plants all operate on the same principle - magnets plus copper wire plus motion equals electric current. The electricity produced is the same, regardless of source. A power station (also referred as power plant) is an industrial facility for the generation of electric power. At the center of nearly all power stations there is a generator, a rotating machine that converts mechanical power into electrical power by creating relative motion between a magnetic field and a conductor [15].

Electric power *transmission* is the bulk transfer of electrical energy, from generating power plants to electrical substations located near demand centers. Substations transform voltage from high to low, or the reverse, between the generating station and consumer, electric power may flow through several substations at different voltage levels. Transmission lines, when interconnected with each other, become transmission networks [8].

Electricity *distribution* is the final stage in the delivery of electricity to end users. A distribution system's network carries electricity from the high-voltage transmission system and delivers it to consumers. The distribution infrastructure is extensive, after all, electricity has to be delivered to customers concentrated in cities, suburbs and very remote regions. [40].

The generation, transmission and distribution structure that make up the electric power grid is illustrated in the Figure 2.1. The power is generated in the power plants, the electricity is transmitted in high-voltage through the transmission system until the substations, after that the electricity is reduced to lower voltages and distributed through distribution system to the consumers. All this structure make up the electric power grid.

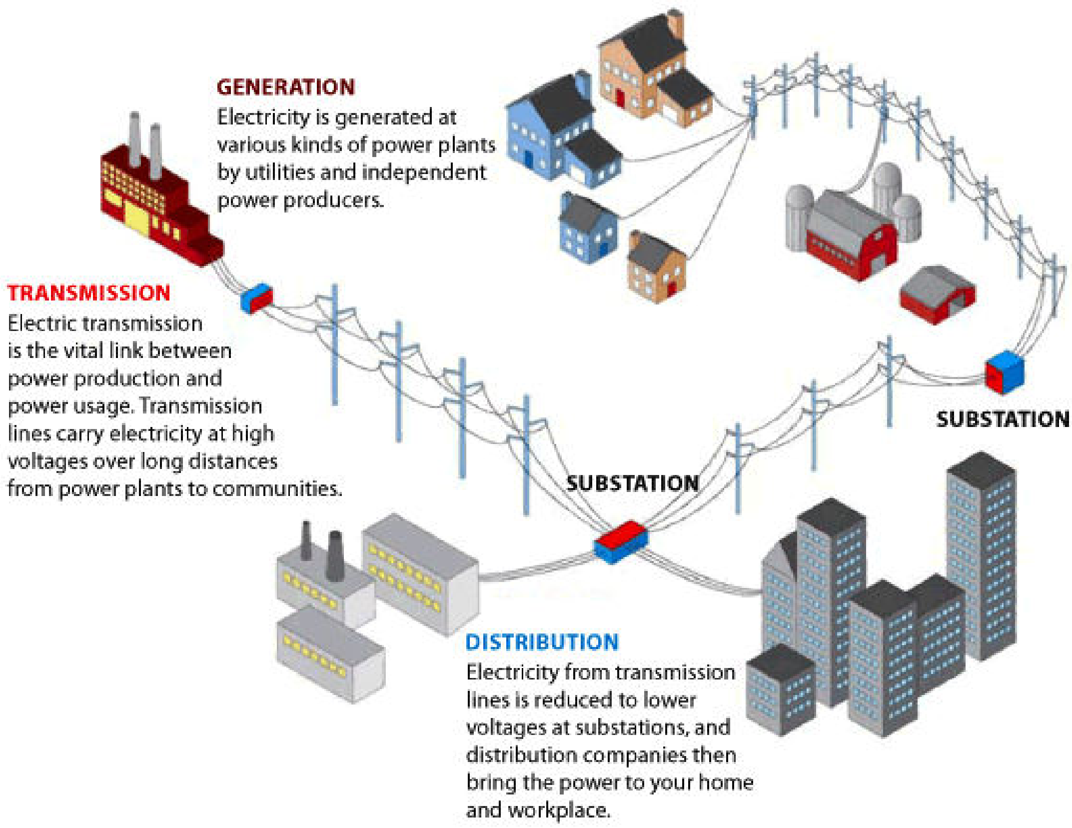

Figure 2.1 – Generation, Transmission and Distribution Grid Structure within the Power Industry [41]

2.2 Smart Grid

Smart grid generally refers to a class of technology using computer-based remote control and automation. These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries [33]. Murphy et al. [32] define the term *Smart Grid* as a modern electricity system that uses uses sensors, monitors, communication, automation and computers to improve the exibility, security, reliability, efficiency and safety of the electricity system.

The seven principal characteristics of the smart grid are [21]:

- Enables active participation by consumers: Consumer choices and increased interaction with the grid bring tangible benefits to both the grid and the environment, while reducing the cost of delivered electricity.
- Accommodates all generation and storage options: Diverse resources with plug-and-play connections multiply the options for electrical generation and storage, including new opportunities for more efficient, cleaner power production.
- Enables new products, services, and markets: The grids open-access market reveals waste and inefficiency and helps drive them out of the system while offering new consumer choices

such as green power products and a new generation of electric vehicles. Reduced transmission congestion also leads to more efficient electricity markets.

- Provides power quality for the digital economy: Digital-grade power quality for those who need it avoids production and productivity losses, especially in digital-device environments.

- Optimizes asset utilization and operates efficiently: Desired functionality at minimum cost guides operations and allows fuller utilization of assets. More targeted and efficient maintenance programs to the grid result in fewer equipment failures and safer operations.

- Anticipates and responds to system disturbances (self-heals): The smart grid performs continuous self-assessments to detect, analyze, respond to, and as needed, restore grid components or network sections.

- Operates resiliently against attack and natural disaster: The grid deters or withstands physical or cyber attack and improves public safety.

The deployment of technology solutions that achieve these characteristics can improve how the smart grid is planned, designed, operated, and maintained. Smart meter is one of the technologies that constitute the smart grid; the smart meter makes possible to extract value from two-way communication in support of distributed technologies and consumer participation [33].

The benefits of the smart grid are substantial. These benefits results from improvements in the following six key value areas [21]:

- **reliability**: by reducing the cost of interruptions and power quality disturbances and reducing the probability and consequences of widespread blackouts;

- **economy**: by keeping downward prices on electricity prices, reducing the amount paid by consumers;

- **efficiency**: by reducing the cost to produce, deliver, and consume electricity, while providing the same or better level of quality service;

- **environmental**: by reducing emissions through enabling a larger penetration of renewables and improving efficiency of generation, delivery, and consumption;

- **security**: by reducing the probability and consequences of manmade attacks and natural disasters; and

- **safety**: by reducing injuries and loss of life from grid-related events.

Ramchurn et al. [35] argue that the smart grid provides significant new challenges for research in AI since these technologies will require algorithms and mechanisms that can solve problems involving a large number of highly heterogeneous actors. Demand-Side Management, electric vehicles, virtual power plants, energy prosumers and self-healing networks are some of the key components that deserve attention in smart grid research.

Schweppe et al. highlight reasons why demand for electricity should be made more adaptive to supply conditions [39]. They note that if peaks of demand were flattened, it would result in longer term and cheaper production contracts, resulting in a more efficient grid with lower prices for consumers.

2.2.1 Demand-Side Management

A safe and efficient electricity grid should be in perfect balance. Schweppe et al. highlighted reasons why demand for electricity should be made more adaptive to supply conditions [39]. They noted that if peaks of demand were flattened, it would result in longer term and cheaper production contracts, resulting in a more efficient grid with lower prices for consumers.

Demand-side management (DSM) is used to describe the actions of a utility, with the objective of altering the end-use of electricity, whether it be to increase demand, decrease it, shift it between high and low peak periods, or manage it when there are intermittent load demands. In other words DSM is the implementation of measures that can help the customers to use electricity more efficiency.

Existing approaches to reduce demand have been limited to either directly controlling the devices used by the consumers (e.g., automatically switching off high load devices such as air conditioners at peak times), or to providing customers with tariffs that deter peak time use of electricity. With the deployment of smart meters, it is possible to make real-time measurements of consumption, providing every home and every commercial and industrial consumer with the ability to automatically reduce load in response to signals from the grid.

An important AI challenge in demand-side management is designing automation technologies for heterogeneous devices that learn to adapt their energy consumption against real-time price signals when faced with uncertainty in predictions of future demand and supply.

2.2.2 Electric Vehicles

Electric vehicles (EV) are becoming more viable. In the coming years we are likely to see the large-scale adoption of electric vehicles that will shift the energy requirements of transport from fossil fuels to renewable electricity from the smart grid. EVs place a considerable additional load on the grid due to the high charging rates. While a typical house may use between 20 to 50 kWh of energy per day, an EV battery may be charged with 32 kWh of energy in just a few hours [18]. The Figure 2.2 shows an EV connected at the home charging device.

Figure 2.2 – An Electric Vehicle [19]

Consequently, an important AI challenge in the deployment of Electric Vehicles in the smart grid is to design decentralized control mechanisms that coordinate the movement of Electric Vehicles (with different battery capacities and charging speeds) to different charge points by providing incentives to consumers to do so. These mechanisms can maintain secure flows on the grid and ensure that transformers do not trip due to excess demand.

2.2.3 Virtual Power Plants

As larger numbers of actors (e.g., Electric Vehicles, households, or renewable energy providers) in the smart grid communicate and coordinate with each other to control demand at different points in the network, it is important to harness synergies that exist between them to improve the efficiency of the grid. For instance, using demand-side management to ensure that demand is able to follow the supply of renewable energy, and EV discharging to the grid to cope with excess demand. Other example is: Electric Vehicle discharging to satisfy demand at times when demand-side management techniques cannot shift enough usage to later times.

A Virtual power Plant, as the name implies, is not an actual physical power plant, but rather, it denotes the coming together of small scale distributed generating resources that can be utilized as a conventional generator. The individual actors need to synchronize their heterogeneous services within the VPP agility so as to meet the requirements of the contracts they make with their customers. These technical arrangements may need to be specified on a daily, and even on an hourly basis to maximize the profits of the individual actors.

Figure 2.3 illustrates a Virtual Power Plant with a group of households using photovoltaic cell to generate energy, an Electric , a hydroelectric plant, some wind turbines, and a commercial building as well. Connecting the entities there is a power transmission system, and in the center a control center to coordinate the Virtual Power Plant.

Figure 2.3 – Virtual Power Plant [25]

There is a number of relevant points in the VPP field. First, the management of VPPs coordinates a number of heterogeneous actors to maximize the amount of energy delivered in the system while minimizing the costs and uncertainties. Second, the negotiation between each potential member of a VPP, since each one is motivated to maximize its own profit, even though, as a group they compete against other actors. Third, VPPs require the definition of computationally efficient search algorithms to allocate the payoffs to individual members of VPPs, while taking into account uncertainty in defining the relative contributions of each member to the aggregated performance of the VPP.

In order to address these issues, the following challenge needs to be overcome: the design of agent-based models of different VPP actors and processes in order to capture the complexity of the technical arrangements needed to form and manage VPPs.

2.2.4 Energy Prosumers

Prosumer is a combinations of the word **pro**ducer with the word con**sumer** (Figure 2.4). Energy Prosumer in the power market applies to entities that consume energy and can also produce energy. In a smart grid a prosumer can be a new and active participant in balancing the electricity system.

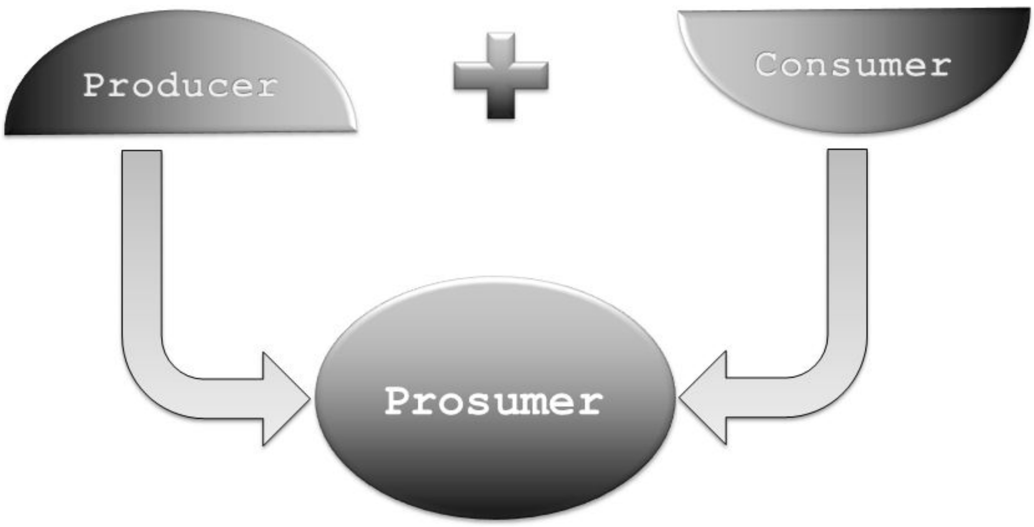

Figure 2.4 – Prosumer = Producer + Consumer

Compared to typical consumers who are mainly concerned with optimizing their electricity usage, prosumers need to optimize both production and consumption of energy in order to make trading decisions in real-time, through internet-based interfaces to spot or forward markets, so that they maximize the profits they can make by buying (to consume or store) and selling energy (either energy that they generate, or have stored earlier).

In summary, challenges providing intelligent control mechanisms for prosumers to trade in electricity markets whilst ensuring safe network flows include: developing computationally efficient learning algorithms that can accurately predict both the prosumers consumption and generation profiles and developing human-agent interaction mechanisms, to allow prosumers to guide their agents' trading decision, that take into account the prosumers' daily constraints and preferences to consume or produce energy.

2.2.5 Self-Healing Networks

Decentralized control strategies and fault-correction mechanisms should be considered in scenarios with complex networks. Nowadays network operators already rely on a number of intelligent systems to prevent faults and repair the grid. However, in a grid with a large number of heterogeneous prosumers operating and varying the network conditions more rapidly, such network operators and their intelligent systems need to be improved to cope with a more dynamic energy market. For example, if voltages tend to drift in some parts of the network, automatic actions on transformers may be taken to re-establish the correct voltage levels, or assistance may be requested from storage that is currently plugged into the network [35].

In our opinion, an important AI challenge of self-healing mechanisms is to enable distributed coordination of automatic voltage regulators and energy providers and consumers for voltage control and to balance demand and supply during recovery from faults.

2.3 Microgrid

Distributed generation located close to demand delivers electricity with minimal losses. The use of renewable distributed generation, the dependency on fossil fuels and on their price can be minimized, therefore this power may have a higher value than power coming from large, central conventional generators through the traditional utility transmission and distribution infrastructure. This step will also lead to a significant reduction of carbon dioxide emissions, which is required by several government programs.

An intentional island grid (**Microgrid**) can be defined as an aggregation of loads and sources capable of operating independently from a larger electric grid, while providing continuous power [2]. An intentional island grid is a regionally limited system of distributed energy resources, consumers and optionally storage. Microgrids use a variety of energy, communications and computer technologies to allow the consumers served by them to meet all, or a large portion, of their total energy needs with devices that form part of the microgrid [32].

Microgrids can quickly switch between operating on and off the grid, for example: when the grid offers cheap electricity, the Microgrid can purchase it, but if prices rise or there is a power failure, the microgrid can isolate itself [27]. Many small (less than 250 kW) generation and storage technologies are already being used to avoid peak generation and provide back-up generation during power system outages [28].

Figure 2.5 shows groups of electricity generation (photovoltaic cell and wind turbine) and energy storage operating together with traditional centralized grid (macrogrid). The single point of common coupling with the macrogrid can be disconnected once it become unreliable. From the point of view of the grid operator, a connected microgrid can be controlled as if it was one entity.

Microgrids can be considered the building blocks of a smart grid. The purpose of setting up a microgrid is to continue providing power during power system disturbances and blackouts. This is referred to as *islanding*. In a normal scenario microgrids are capable of operating interconnected with the entire power grid, providing excess real power and assist in voltage support to the greater power system. When islanded from the utility due to abnormal grid conditions (e.g. fault or maintenance conditions), the microgrid must be able to regulate and sustain its own power delivery [10].

Therefore, it is possible observe relevant challenges related a microgrid systems like how to improve energy production and delivery for local customers, while facilitating a more stable electrical infrastructure with benefits toward environmental emissions, energy conservation, and operational cost [11]. Other challenge is how to provide sufficient generation capacity, controls, and operational

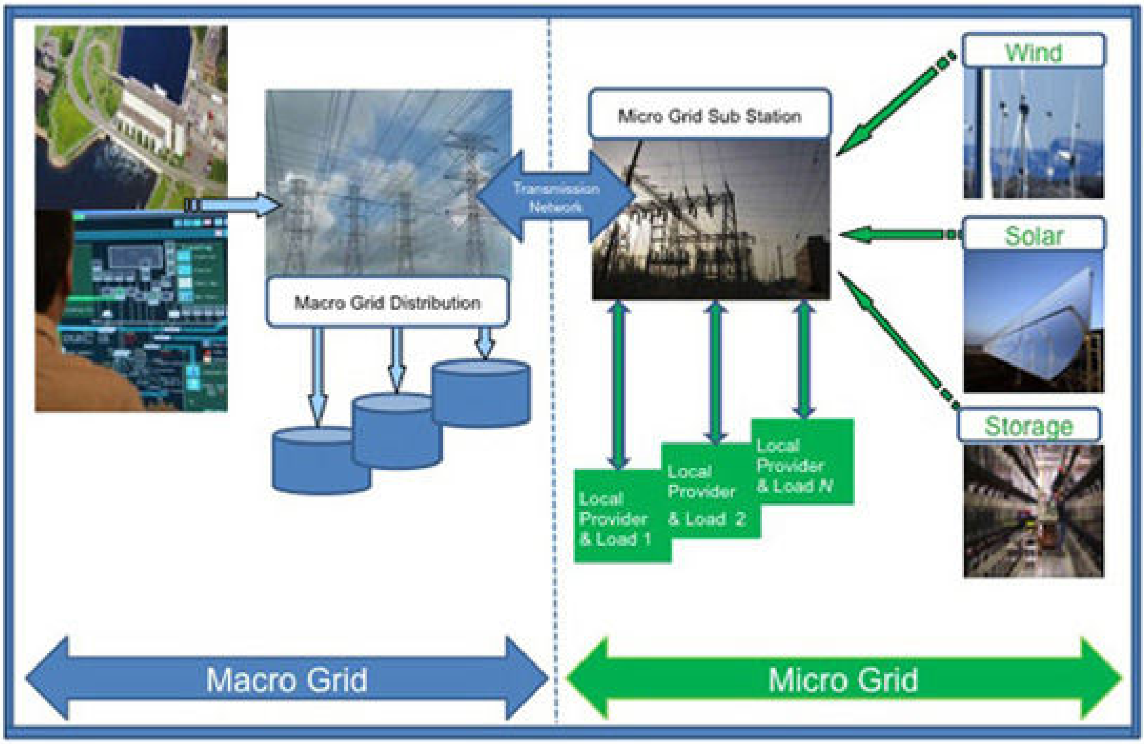

Figure 2.5 – Macro grid and Micro Grid connection [16]

strategies for some time after being disconnected from the distribution system and remain operational as an autonomous entity [26].

2.4 Smart Home

Smart home is the term commonly used to define a household that has appliances capable of communicating with one another and can be operated remotely by a control system. This control system allows the definition schedules for operation or remote operation by phone or over the internet.

Within a smart home, a smart meter is responsible for providing the interface between household and the energy provider. Replacing the old electromechanical meter, these meters operate digitally, and allow for automated and complex transfers of information between the household and the energy provider. For instance, smart meters can receive signals from the energy provider to help the household balance demand and reduce energy costs. Smart meters also provide utilities with more information about how much electricity is being used [17].

A smart appliance is a device that allows access and operation through an automated management system. Smart appliances can also be able to respond to signals from the smart meter to avoid using energy during times of peak demand. This new generation of household devices can be distinguished by three characteristics [1]:

- **instrumented**, devices provide increasingly detailed information about and control over their own operation and also provide information about the environment in which they operate;

- **interconnected**, devices can communicate and interact, with people, systems and other devices. It supports the aggregation of information and control of devices throughout the network; and

- **intelligent**, devices can make decisions based on data, leading to better outcomes, supporting the optimization of their use, both for the individual consumer and for the service provider.

Current smart appliances and their communications technology are very heterogenous among different vendors, with standardization in its early phases. In this scenario of heterogeneous devices and protocols, it is necessary to adopt an abstract, standards-based view of the new smart grid system as early as possible. In an ideal smart grid environment, all smart grid appliance functions, device connectivity, and device protocols are be standardized in order to avoid multiplied maintenance effort and vendor lock-in for proprietary components [38].

One challenge to the realization of the smart home vision is the need to integrate a large number of entity interfaces, networking protocols and technologies and a variety of applications and services already deployed in the home today. Two types of communication protocols may be considered. The first one is LAN-like protocols to enable appliances to communicate with each other inside of the household. The second type of communication protocol is a WAN-like, this protocol allow a wider communication with other elements of the power grid. For example, each household appliance can take advantage of the household router to connect directly to service in the network [1].

The deployment of a smart home goes beyond the improvement of a household, for example, if a set of smart homes work together it is possible avoid peak of demand in the whole power grid. For instance, a smart air conditioner might extend its work time slightly to reduce its load on the grid; while not noticeable to the user, millions of air conditioners acting the same way could significantly reduce the load on the power grid. Likewise, a smart refrigerator could defer its defrost cycle until off-peak hours, or a smart dishwasher might defer running until off-peak hours.

A smart home can use a micro generation system (e.g. Rooftop solar electric systems, small wind turbines) to supply the household demand. Moreover, smart homes with their controls system can help to effectively connect all micro generating systems to the grid. For instance, a community of smart homes with photovoltaic panels can use their solar array to keep the lights on even when there is no power coming from the grid. Figure 2.6 illustrates a smart home system with its own micro generation of renewable energy, a storage unit used to store power to be consumed later, an electric vehicle, a smart meter communicating with the utility system.

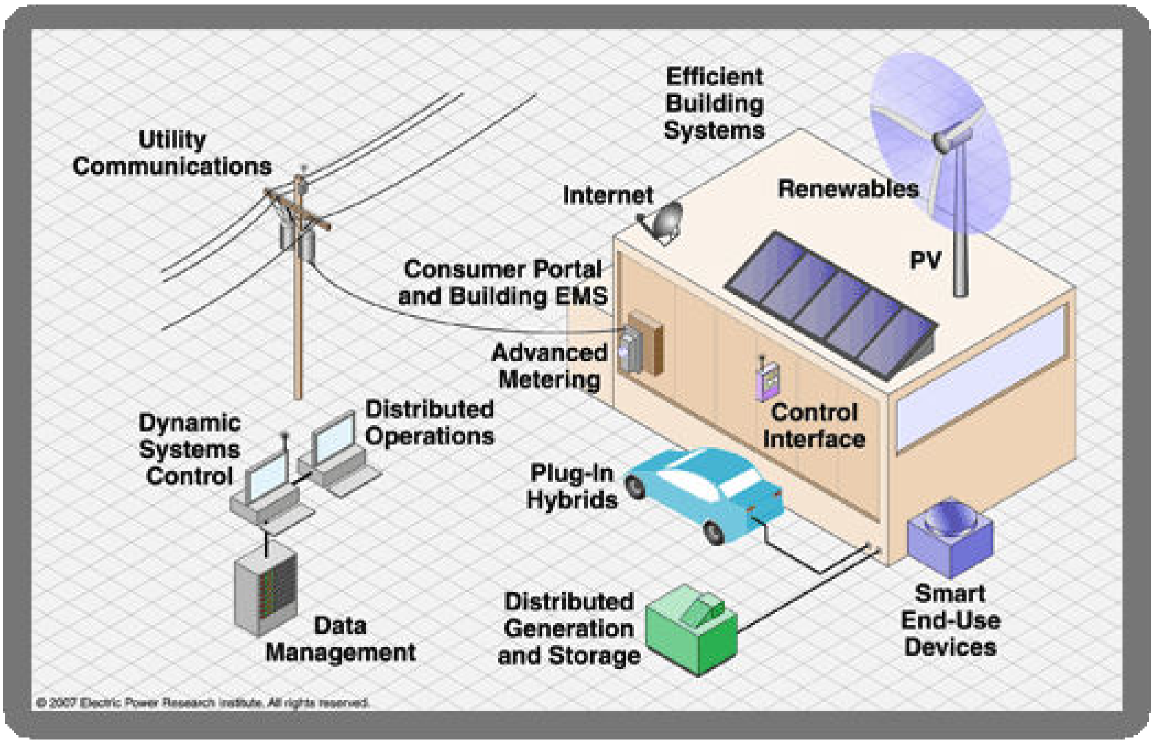

Figure 2.6 – Smart Home [25]

2.5 Software Agents

According Wooldridge [45], 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. A software agent is viewed as a autonomous that is able to operate without user intervention, having the ability to communicate with others and to monitor and understand the environment in which it inserted [22].

In general software agents can be defined as programs that operate independently from external control. The main difference between conventional software and software agents is the issue of autonomy. An agent is able to communicate with other agents and users, and also react to changes in their environment, always seeking to achieve its goals, whereas conventional software is not goal oriented.

Other important difference [44] is that software agents are situated in a specific environment and able to interact continuously with the environment through perceptions and actions. For Hayes [22] intelligent agents must be able to perform the following functions: perceiving dynamic conditions in their environment; take action to modify conditions in their environment; reasoning to interpret perceptions, solve problems, trace inferences, and determine actions. Software agents can do many activities, being able to search for information on the network, manage schedules, negotiate simple intentions, etc. However, their development requires a high degree of knowledge and its programming is complex.

Perceptions are the inputs of the agent about which events are happening in the environment, and actions are the outputs of the agent which is reflected in changes in the environment. A well know model of agents is the BDI (Beliefs - Desires and Intentions) model. The main objective this model is to allow the characterization of agents using anthropomorphic notions, such as mental states and actions. These notions and their properties can also be studied and defined by modal logics that support the formal analysis, specification and verification of the characteristics of rational agents [6].

A good explanation for BDI model is: if the agent figure out a change, starts to *believe* that something is true, and in reaction to this change, it starts to *want* to do something according to an *intention* projected. With a set of beliefs, desires and intentions it interacts with the environment of execution and choose one or more actions consistent with your rules and beliefs in order to achieve their goals.

2.6 BDI Architecture

The BDI model of human practical reasoning was originally developed by Michael Bratman [7] as a way of explaining future-directed intentional reasoning. It was later adapted into a model for programming intelligent agents by characterizing an agent in terms of three mental states: beliefs, desires and intentions. *Beliefs* represent the informational state of the agent, in other words its beliefs about the world (including itself and other agents); *Desires* represent the motivational state of the agent. They represent objectives or situations that the agent *would like* to accomplish or bring about; and *Intentions* are a subset of the list of desires that is selected to be adopted.

Many popular implementations of the BDI architecture rely on the following components (illustrated in Figure 2.7), as proposed by Wooldrigde [43]. There are seven main components to a BDI agent, structured as follows:

- Belief revision function, (brf): which takes a perceptual input and the agent's current beliefs, and on the basis of these, determines a new set of beliefs;
- A set of current beliefs: representing information the agent has about its current environment, about the agents present in the environment and about itself;
- An option generation function (options): which determines the options available to the agent (its desires), on the basis of its current beliefs about its environment and its current intentions;
- A set of current options: representing possible courses of actions available to the agent;
- A filter function (filter): which represents the agent's deliberation process, and which determines the agent's intentions on the basis of its current beliefs, desires, and intentions;

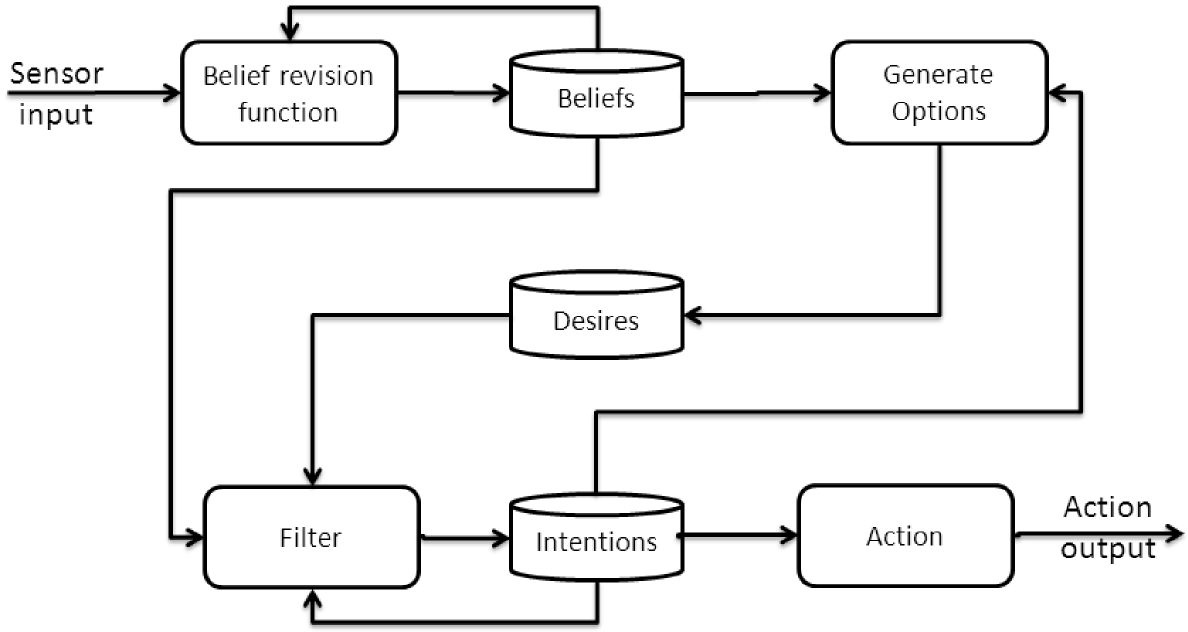

Figure 2.7 – Belief-desire-intention architecture [43]

- A set of current intentions: represent the deliberative state of the agent, what the agent has chosen to do. Intentions are desires to which the agent has to some extent committed. In implemented systems, this means the agent has begun executing a plan.

- An action selection function (execute): which determines an action to perform on the basis of current intentions.

2.7 AgentSpeak Language

AgentSpeak(L) is a programming language based on a restricted first-order language with events and actions, It was first presented in [36] . It is a natural extension of logic programming for the BDI agent architecture, and provides an abstract framework for programming BDI agents. The current state of the agent, its environment, and other agents, can be viewed as its current belief state; states which the agent wants to bring about based on its external or internal stimuli can be viewed as desires; and the adoption of programs to satisfy such stimuli can be viewed as intentions.

The alphabet of the formal language consists of variables, constants, function symbols, predicate symbols, action symbols, connectives, quantifiers, and punctuation symbols. Apart from first-order connectives, we also use ! (for achievement), ? (for test) and ; (for sequencing),

An AgentSpeak(L) agent is created by the specification of a set of base beliefs and a set of plans. A belief atom is simply a first-order predicate in the usual notation, and belief atoms or their negations are belief literals. An initial set of beliefs is just a collection of ground belief atoms.

AgentSpeak(L) distinguishes two types of goals: *achievement* goals and *test* goals. Achievement goals are predicates (as for beliefs) prefixed with the '!' operator, while test goals are prefixed with the '?' operator. Achievement goals state that the agent wants to achieve a state of the world where the associated predicate is true. A test goal states that the agent wants to test whether the associated predicate is one of its beliefs (i.e., whether it can be unified with a predicate in that agents base beliefs).

Triggering event is a very important concept in this language. Triggering events define which events may initiate the execution of plans. An event can be internal, when a subgoal needs to be achieved, or external, when generated from belief updates as a result of perceiving the environment. There are two types of triggering events: those related to the addition ('+') and deletion ('-') of mental attitudes (beliefs or goals).

Plans refer to the basic actions that an agent is able to perform on its environment. Such actions are also defined as first-order predicates, but with special predicate symbols (called action symbols) used to distinguish them. The actual syntax of AgentSpeak(L) programs is based on the definition of plans. Recall that the designer of an AgentSpeak(L) agent specifies a set of beliefs and a set of plans only [4].

```
+concert(A,V) : likes (A)
        <-!book_tickets(A,V).

+!book_tickets(A,V) : ~busy(phone)
        <- call(V);
        ...;
        !choose_seats(A,V).
```

Listing 1: Examples of AgentSpeak(L) Plans

Listing 1 shows a examples of AgentSpeak(L) plans. The first plan tell us that, when a concert is announced for artist A at venue V (a belief concert(A,V) is added from perception of the environment), then if this agent in fact likes artist A, then it will have the new goal of booking tickets for that concert. The second plan tells us that whenever this agent adopts the goal of booking tickets for A's performance at V, if it is the case that the telephone is not busy, then it can execute a plan consisting of performing the basic action call(V) (assuming that making a phone call is an atomic action that the agent can perform) followed by a certain protocol for booking tickets (indicated by '. . .), which in this case ends with the execution of a plan for choosing the seats for such performance at that particular venue [5].

2.8 JaCaMo

JaCaMo is a framework for Multi-Agent Programming that combines three separate levels of abstraction. Each level of abstraction in JaCaMo has its own description language and programming model. A JaCaMo multi-agent system or, equivalently, a software system programmed in JaCaMo is defined by a **Moise** organization of autonomous BDI agents based on concepts as roles, groups, mission and schemes; autonomous agents implemented in **Jason**; working in shared distributed artifact-based environments developed in **CArtAgO**. The JaCaMo meta-model defines dependencies, connections and, more importantly, conceptual mappings and synergies between all the different abstractions available in the meta-models associated to each level of abstractions [3].

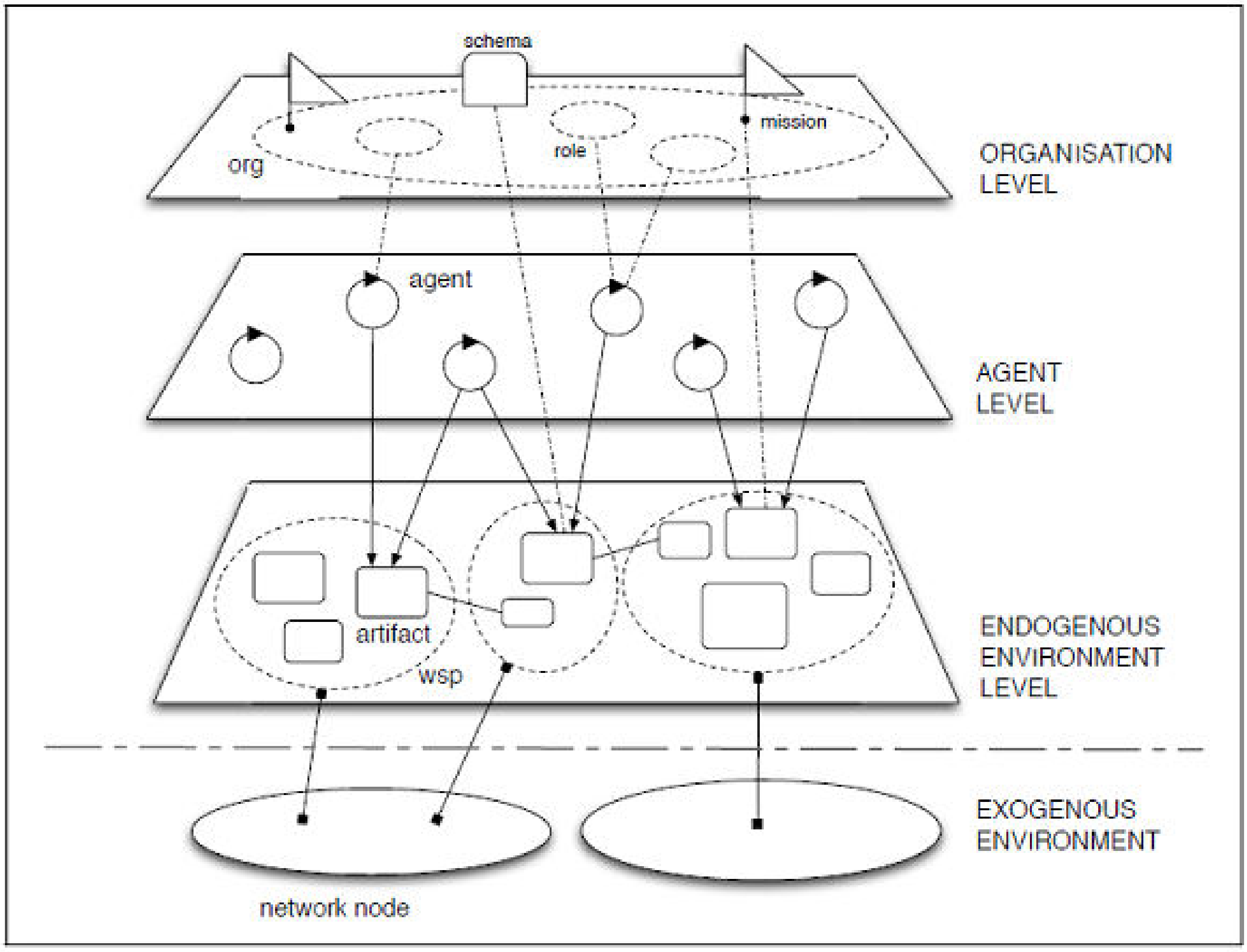

Figure 2.8 – Jacamo Approach

Jason is a concrete implementation of an AgentSpeak language interpreter released as an open source software developed in Java, which is based on the BDI architecture [6] and allows the customization of most aspects of an agent or a multi-agent system.

CArtAgO (Common ARTifact infrastructure for AGents Open environments) makes it possible to develop and execute artifact-based environments, structured in open workspaces (possibly distributed across the network) that agents of different platforms can join so as to work together within such environments [37].

Moise is used to specify an organization from three points of view: structural, functional, and deontic dimensions. The structural dimension specifies the roles, groups, and links of the organization. The definition of roles states that when an agent decides to play some role in a group, it is accepting some behavioral constraints related to this role. The functional dimension specifies how the global collective goals should be achieved, i.e. how these goals are decomposed (in global plans), grouped by missions to be distributed to the agents. The decomposition of global goals results in schemes, where the leaves-goals can by achieved individually by the agents. The deontic dimension is added in order to connect the structural dimension with the functional by the specification of the roles permissions and obligations for missions [23].

Figure 2.8 illustrates the three levels of JaCaMo. Moise is responsible for the *Organization Level*; Jason defines the behavior of individual agents in the *Agent Level*; and CArtAgO level is used to develop virtual environment in the *Environment Level*.

2.9 Related Work

This section describes some important and relevant research in smart grid management and multi-agent systems, including current approaches and related research.

Ramchurn et al. in [35] introduce the smart grid key components: demand-side management, electric vehicles, virtual power plants, the emergence of prosumers, and self-healing networks. Demand-side management is directly related to this dissertation research, in Section 5 we describe a mechanism to manage the power consumption by the demand-side. In the paper *Putting the 'smarts' into the smart grid: a grand challenge for artificial intelligence* the authors argue about the smart grid new challenges in artificial intelligence and the smart grid technologies that require algorithms and mechanisms to solve problems involving a large number of heterogeneous actors. There is a tendency in the developed world to decrease the use of fossil fuels and move to a low-carbon economy to guarantee energy security and mitigate the impact of energy use on the environment. This transition requires a fundamental re-thinking and re-engineering of the smart grid which must be able to make efficient use of renewable energy sources and support the additional electricity required by new actors like electrical vehicles. Many of the issues within the smart grid can be found in other domains such as water distribution, transportation, and telecommunication networks. So, there is potential to transfer technologies across these domains and also address smart grid issues that affect the sustainability of such systems.

Voice et al. in [42] describe a decentralized control mechanism to manage micro-storage in the smart grid is proposed. The approach introduced in this paper uses an adaptive pricing scheme that energy suppliers apply to home smart agents controlling micro-storage devices. The authors propose a market strategy that allows the supplier to reduce wholesale purchasing costs without increasing the uncertainty and variance for its aggregate consumer demand. Theoretical results are shown proving the stability and profitability go the algorithm introduced in this paper. In a realistic scenario the mechanism reduces consumer costs by 16%, and further, it is stable against dramatic short term changes in the system.

Ramchurn et al. in [34] introduce as agent-based control to optimize the use of devices and heating in the smart home while interacting with the grid. The decentralized demand-side management mechanism allows agents to coordinate in a decentralized way, by adapting the deferment of their loads based on grid prices. The model introduced in this paper aims to coordinate a large populations of autonomous agents representing individual smart meters. The simulations involve 5000 homes and using average (winter) load profiles for 26M homes in the UK, and the results shown that the model could improve grid performance by reducing carbon emissions up to 6% and peaks of demand by to 17%.

As described in Section 2.8 the JaCaMo framework uses the Moise model to specify MAS organizations, like roles that the agents may play and goals to which the agents can be committed. Similarly to the JaCaMo framework the Generalized partial global planning (GPGP) coordination framework [14] was developed to maximize the combined utility accrued by the group of agents as a result of successful completion of its high-level goals. These goals can be independent or held jointly by two or more agents, the goals can also be time and resource sensitive, and be of different utilities. GPGP is designed to be applicable in a wide range of environments and task domains and dealing with the coordination of agents. The framework development was influenced by two factors: the first factor is to generalize and make domain independent the coordination techniques of the partial global planning (PGP) framework; the second factor is based on viewing agent coordination in terms of a distributed search of a dynamically evolving the goal tree. The goal tree specifies a set of subgoals that need to be solved to solve the top-level goal.

Finally, the TAEMS framework [13] provides a modeling language used to model complex computational task environments that is compatible with both formal agent-centered approaches and experimental approaches. This framework describes the tasks that the agent may perform and allows us simulate the behavior of the agents with respect to interesting characteristics of the computational task environments of which they are part. Such structures are represented by graphs, containing goals and sub-goals that can be achieved, along with methods required to achieve them. Each agent has its own graph, and tasks can be shared between graphs, creating relationships where negotiation or coordination may be of use. Coordination in TAEMS has to be identified using the syntax of language and then employ some kind of adhoc coordination by using commitment constructs that are available. The TAEMS framework does no explicit planning, its focus is on coordinating tasks of agents where specific deadlines may be required, and its development has been discontinued since 2006.

In this chapter we introduced a brief background on smart grid and intelligent agents, focusing on Multi-Agent Systems and demand-side management. In the next Chapter we show the profile of consumers of electricity in Brazil and protections to the next years.

3. USER PROFILE IN BRAZIL

Brazil is a country of continental dimensions divided into five geographical areas: Northern, Northeast, Midwest, Southeast and Southern. Each of these geographic areas has different social, economic and environmental characteristics. These characteristics affects the way in which the brazilian residential consumer consumes energy. For instance, the Northern region is economically underprivileged compared to the other regions, so residential consumers in the Northern consume less energy than the rest of the country.

The Midwest is the second largest region of Brazil in territorial surface. On the other hand, it is the least populated region of the country and has the second lowest population density, behind only the Northern region.

The Southeast is the most populous and wealthy region of Brazil and is responsible for 56% of the Gross Domestic Product (GDP). It occupies 10% of the Brazilian territory and concentrates over 46% of all residential consumers in the country. These residential consumers consume over 52% of all residential energy produced.

This chapter defines the residential consumer units, presents the average of consumption in Brazil and shows some projections to the next years. The information introduced in this chapter helped in the construction and validation of the smart home model. Using this information we defined the user profiles, the home profile and the scenarios setup used in the simulations.

3.1 The Residential Consumer Units

Consumer or Customer or end-user shall mean any person who is the registered customer of the utility being supplied with electricity by the concerned distribution utility or any person authorized by the registered customer to occupy the premises and enjoy electric service. In this context the consumer unit is an electrical installation characterized by receiving electricity from the distribution utility, with individual metering and corresponding to a single consumer [12]. Some examples of consumer units are: a household, an industrial building, an office inside a commercial building or a farm. The Residential consumer unit shall mean a customer classified as such in the distribution utility

The number of residential electricity consumer units from 2004 to 2012 can be seen in the Table 3.1. This Figure shows the number of consumer units divided per region. As Southeast region is the most populated region in Brazil, it concentrates up to 46% of all consumers units.

Figure 3.1 shows the growth of consumers units in Brazil. In 2004 the Brazil had over five hundred and fifty million (550,000,000) consumer units and in 2012 the number of consumer units was almost seven hundred and thirty million (730,000,000). From 2004 to 2012 the number of consumer units grew 32% in the country.

Table 3.1 – Residential Electricity Consumer units from 2004 to 2012

Number of electricity consumers (x1000)									
	2004	2005	2006	2007	2008	2009	2010	2011	2012
TOTAL	**554,440**	**575,113**	**594,922**	**614,442**	**639,351**	**660,872**	**684,683**	**708,995**	**729,947**
Region									
Northern	28,424	29,452	30,709	32,215	33,644	35,141	36,970	39,040	41,034
Northeast	133,154	138,809	145,425	152,432	160,464	168,854	178,283	186,823	192,946
Southeast	271,490	281,374	289,794	296,962	308,106	315,772	323,572	332,062	339,353
Southern	82,062	84,592	86,735	89,066	91,597	93,943	96,934	100,085	103,226
Midwest	39,310	40,886	42,259	43,767	45,540	47,162	48,924	50,984	53,389

The number of consumer units in Southeast region grew 25% in these 9 years and the number of residential consumer units in Northeast region grew over the national average achieving almost 45% of growth. The Northern region is the largest region in Brazil and represents about 42% of the country, although this region represents only 5,6% of residential consumers.

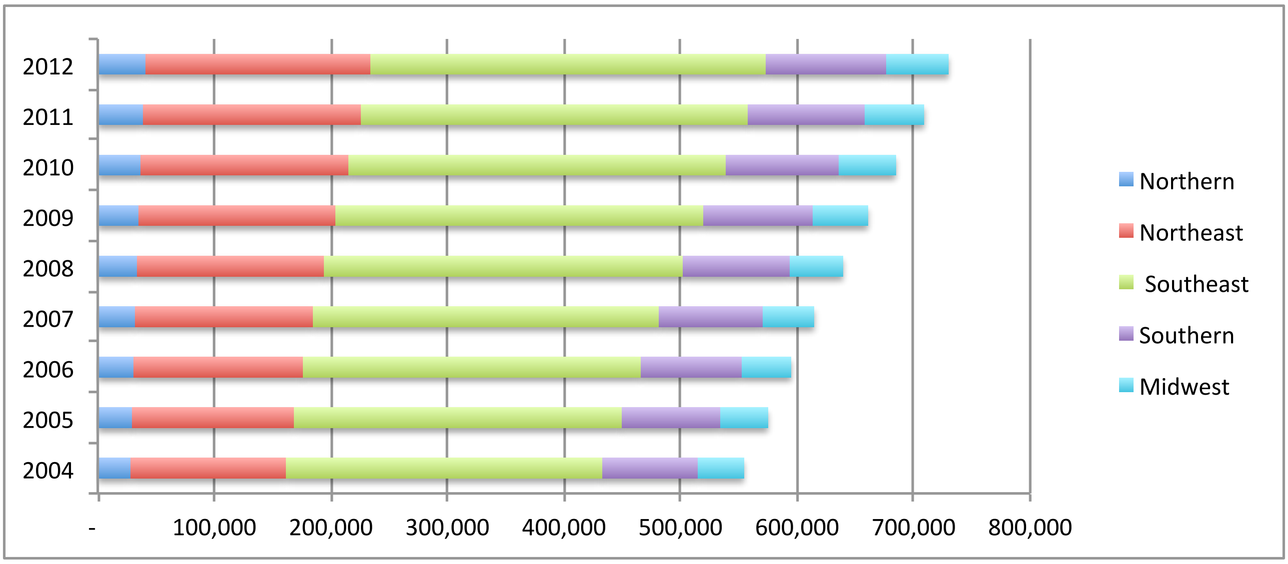

Figure 3.1 – The Growth of Residential Electricity Consumer units from 2004 to 2012 (x1000)

3.2 Annual average of residential consumption in Brazil

According to the Brazilian Energetic Research Company (Empresa de Pesquisa Energetica - EPE) in 2012 Brazil had more than 60,000,000 residential consumers unit and they consumed 117,567,173 Megawatt hours (MWh). It represents an average of 1,933 KWh per residential consumer unit in a year.

The Table 3.2 shows the residential consumption of electricity in 2012 per region in MWh. This table presents how much each region consumed per month. In Figure 3.2 it is possible to see

Table 3.2 – Residential Consumption in 2012 per region

	JAN	FEB	MAR	APR	MAI	JUN	JUL	AGO	SEP	OCT	NOV	DEC	YEAR
TOTAL (MWh)	**9,794**	**9,688**	**10,273**	**9,912**	**9,525**	**9,599**	**9,283**	**9,616**	**9,736**	**9,776**	**10,228**	**10,136**	**117,567**
REGION													
Northern	524	503	503	532	552	566	551	592	603	608	628	598	6,762
Northeast	1,817	1,695	1,830	1,770	1,805	1,765	1,689	1,731	1,714	1,788	1,819	1,871	21,294
Southeast	5,139	5,103	5,476	5,309	4,955	5,035	4,830	4,979	5,107	5,068	5,370	5,223	61,594
Southern	1,584	1,658	1,707	1,534	1,461	1,490	1,504	1,557	1,510	1,489	1,569	1,629	18,693
Midwest	729	728	757	767	753	742	710	758	801	822	842	816	9,224

that the Southeast region consumes more energy than the other regions together and the electricity consumption was balanced during the months of the year 2012.

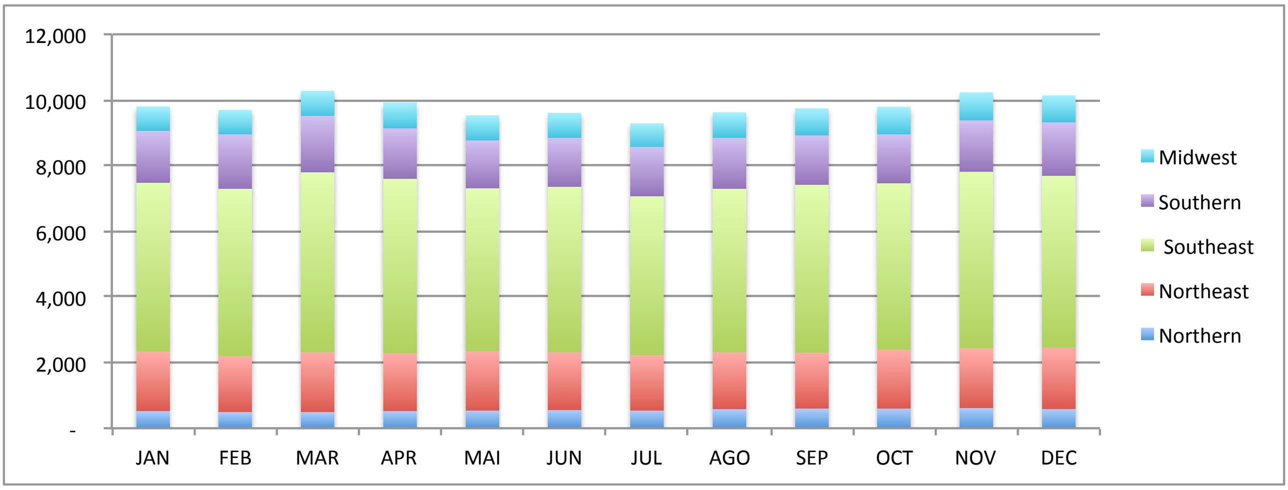

Figure 3.2 – Residential Consumption in 2012 per region

Figure 3.3 presents the residential consumption of electricity in Brazil from 1995 to 2012. In 1995 the residential consumption was 63,576 gigawatts hour (GWh) and in 2012 the residential consumption was 117,567 GWh. It represents an increase of almost 85% in 17 years (in average the residential consumption grows 4.5% by year).

3.3 Consumer units versus consumption

Based on the data presented in sections Section 3.2 and Section 3.1 we can analyze the average of consumption per residential consumer unit in Brazil. Dividing the total of residential consumption by the total of consumer units we can get the consumption per unit which can be represented by the expression below.

$$consumptionPerUnit = (residentialConsumption/TotalUnits)$$

As we described in the previous sections, different regions in Brazil has different consumption profile as well as the residential consumption has been increasing over the years. The Figure 3.4 shows the average of consumption per consumer unit from 2004 to 2012. In 2004 a consumer

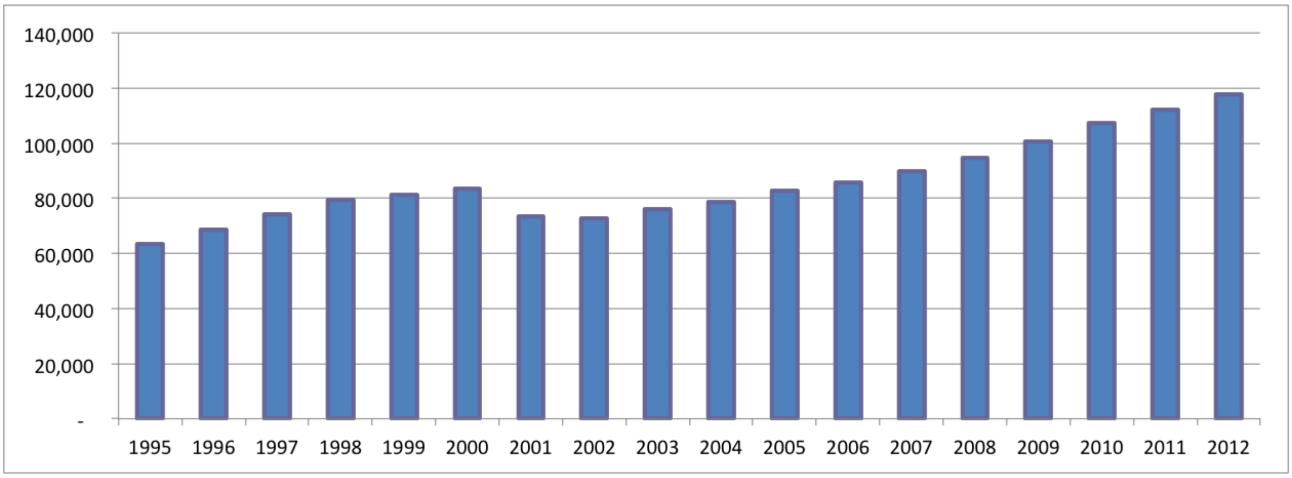

Figure 3.3 – Residential Electricity Consumption from 1995 to 2012

unit in Brazil consumed an average of 6897 kw/h during the whole year; Compared with 2012, there was a increase of almost 15% in 9 years.

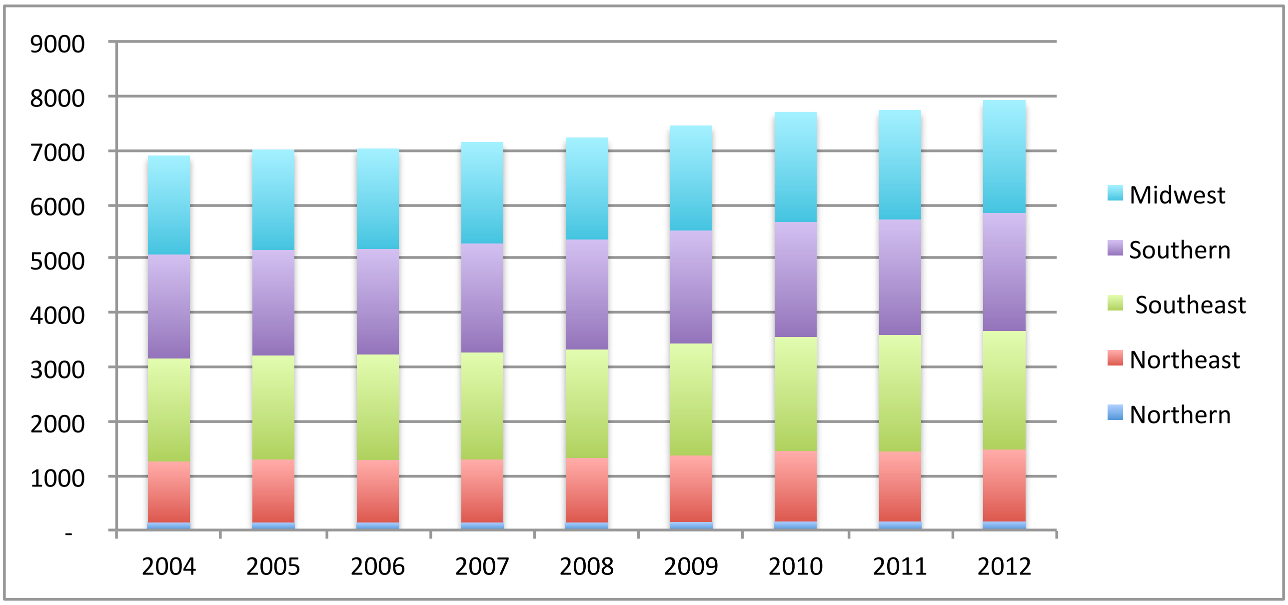

Figure 3.4 – Annual consumption per consumer units (from 2004 to 2012)

The Table 3.3 shows the average of consumption per consumer unit divided per Brazilian regions. As can be seen in this table the region that most consumes energy during the year it is the Southern region, a residential consumer unit in this region consumes in average 2038 kw/h per year and 170 per month. The Southern region is followed by the Southeast region on average of consumption.

The region that consumes the least energy per unit is the Northeast region, a residential consumer unit in Northeast consumes in average 1213 kw/h per year and 101 per month. As a result, we can ascertain that a consumer unit in the Southern region consumes 68% more than a consumer unit in Northeast. A consumer unit in the Southern region consumes in average 182 kw/h in january resulting in a peak of consumption in the first month of the year, otherwise in july a consumer unit in Northeast region consumes just 96 kw/h. As Brazil is a huge country and considering these two boundaries of consumption there is a variation of consumption of almost 90% over the year.

Table 3.3 – Average of consumption per consumer units (from 2004 to 2012)

	JAN	FEB	MAR	APR	MAI	JUN	JUL	AGO	SEP	OCT	NOV	DEC	YEAR	Average
Region														
Northern	150	141	141	145	146	149	149	153	161	160	161	155	1809	151
Northeast	106	100	103	104	101	98	96	97	98	101	104	105	1213	101
Southeast	176	170	174	173	167	163	162	165	168	168	170	170	2025	169
Southern	182	178	176	172	164	165	166	170	167	163	166	169	2038	170
Midwest	162	156	159	163	158	153	150	156	165	167	167	162	1917	160

To validate our model we based the simulations setup in the informations from the Southern region because comparing with the other regions it is the region that consumes more power comparing with the other regions.

3.4 Projection of the demand for electric power

In the residential sector, the dynamic of energy consumption depends on the demographic variables such as population, households and the number of people per household, the average consumption per customer, the GDP and GDP per capita.

The socio-demographic projections required for energy planning considers the Brazilian population by 2010 according to the Census of 2010 (preliminary data). This data were collected by the Brazilian Institute of Geography and Statistics - IBGE [1] based on the identification of demographic trends observed in the last years, like the reduction of fertility and mortality.

Table 3.4 – Brazil. Projection of the population, 2011-2021

Year	10ˆ3 hab.	Variation per year(%)
2011	193.177	--
2016	200,246	0.7
2021	206.167	0.6

Table 3.4 shows the projection of the population for the period 2011-2021. It is estimated that the growth of the population over the next 10 years will be higher in the Northern and Midwest regions increasing the participation of these two regions in the total population of the country.

Between 2011 and 2021 the Brazilian population will increase around 13.0 million. This number is closer to the current population of the state of Bahia (14 million), more than the pop-

[1] http://censo2010.ibge.gov.br/resultados

ulation of Greece (11.2 million, 2008) and slightly less than the population of Chile (16.8 million, 2008) or Holland (16.4 million, 2008).

The number of households is estimated based on the relation inhabitant/household, an indicator whose evolution can be extracted from censuses conducted. Currently a residence is inhabited on average by 3.3 people, although it is estimated that by 2011 this number will decrease to 2.9 people per household.

It is estimated that the evolution of residential electricity consumption is 4.5% in the period of 2011 to 2021, this evolution it is a result from the combination of the growth of the number of consumers and the consumption per consumer. The projection estimates that the number of consumer units will be increased by 2.5% per year and the consumption per consumer will be increased by 1.9% per year. The average of consumption of a residential consumer in 2012 was 161 kWh/month and the consumption by residential consumers in Brazil at the end of 2021 is expected to be around 190 kWh/month.

The survey presented in this chapter helped us to see the impact of our approach in a typical Brazilian household and we used this data to simulate realistic conditions in our experiments.

The increase of power consumption concerns power utilities may not be possible to increase the production and delivery of power at the same rate as the demand grows. An alternative we must consider is to optimize the use of energy produced today avoiding waste. So, the smart home model presented in the next chapter can be used to optimize the use of energy in households.

4. SMART HOME MODEL

Smart grid brings many opportunities to improve the standard power grid, Section 2.2.1 introduces one approach that allows the end users to assume more control over their consumption. In a city where every consumer units have the ability to control their usage of electricity and if all consumer units work to maximize the power consumption it is possible to maximize the use of energy from the power grid.

This chapter introduces the domestic appliances and household profiles. Information about consumer units presented in the previous chapter are used to organize these profiles. The profiles we define in this chapter are used to support the simulations setup explained in chapter 6.

4.1 Domestic Appliances

The estimated average monthly consumption of appliances presented in this work comes from a company which operates in the areas of generation, transmission and distribution of electricity.

Table 4.1 shows a group of appliances for a household used by a family of three. In this table we have the list of appliances, the power each one consume per hour, the amount of each type of appliance that exists in the household, the time that each appliance is switched on daily and the daily consumption of each appliance.

Table 4.1 – Consumption of a household

Appliance	Power (W)	Quantity	Hours per day	kwh
Air conditioner	950	1	2	57
Vacuum Cleaner	1000	1	0,10	3
Laptop Computer	200	2	0,25	3
Clothes Iron	1000	1	0,10	3
Fluorescent bulb	32	6	3	17,28
LED bulb	13	5	3	5,85
Washing machine	600	1	0,25	4,50
Microwave	1400	1	0,05	2,10
Refrigerator	50	1	24	36
Television	150	1	2	9
Roof fan	200	1	3	18

Within the domestic energy domain, it is common to characterize domestic appliances under specific categories: wet and cold appliances, water heating, space heating, cooking and lighting appliances, periodic load and miscellaneous appliances [20] [34]. Table 4.2 illustrates the types of domestic electrical appliances.

The different categories imply different behaviors. Wet appliances typically involve periods of time programmed by the user or a device controller. Cold appliances have continuous demand,

Table 4.2 – Domestic device groups

Type	**Examples**
Wet	Washing machine, tumble dryers, dishwashers
Cold	Refrigerators, fridge-freezers
Lighting	Incandescent light bulbs, led lamps, fluorescent light bulbs.
Cooking	Electric ovens, microwaves, grill, coffee and tea makers, etc.
Temperature Controller	heat pumps, radiators, air conditioners
Periodic Load	laptop computers, cell phones, tablet computers, electric bicycles, battery chargers
Entertainment	television, home theater, radio, etc
Personal Care	hair dryers, electric toothbrushes, electric razors
Miscellaneous	sewing machines, clothes irons, vacuum cleaners, garden equipment, electric blankets, computer printers, slide projectors, etc.

but this demand is associated to weather variation. A refrigerator, for example, needs to keep the temperature around 5 degrees Celsius and cannot be turned off. It also needs more energy in the summer to maintain the desired temperature compared to the energy needed in winter. Conversely, temperature controllers have power consumption related to their usage and user routine, when there are users at home, temperature controllers and water heating have power consumption, otherwise when there is nobody at home they should be off or in a standby state. Finally, lighting, cooking appliances, entertainment, periodic load and miscellaneous are much more dependent on the user lifestyle and preferences.

4.2 Appliances Description

All devices considered in this model have only two possible states, ON and OFF, and change between these states via their internal schedule or an external command. Moreover, we assume that all appliances have similar energy consumption distribution during all the days of the year. Future studies can consider additional states, such as a standby state. Another future study can expand energy consumption profiles within the year, e.g., different consumption for workdays and weekends as well as different consumption during summer and winter. For this model we consider a typical domestic profile with fixed time intervals consisting of single days, divided in cycles of half-hour. Each time slot $t \in \mathrm{T}$ where $\mathrm{T} = 1,...,48$ [42] [34].

Appliances are classified according its daily execution shift, each appliance can be scheduled to operate in one of the six different options. In this model we define that just one option can be chosen and the appliance is not allowed to operate out of its daily execution shift. Table 4.3 illustrates the daily shifts.

Table 4.3 – Daily Execution Shift

Shift	Begin	End	Initial Cycle	Final Cycle
Dawn	00:00	05:59	1	12
Morning	06:00	11:59	13	24
Afternoon	12:00	17:59	25	36
Night	18:00	23:59	37	48
All	00:00	23:59	1	48
Any	–	–	–	–

If an appliance has "Morning" as its daily shift, it can only operate at any time between 6:00 AM to 11:59 AM. Moreover, if an appliance has "All" as its shift it must operate without interruption throughout all cycles, whereas if an appliance has "Any" as its shift, it can operate in any cycle. Finally, each appliance has an operating window, the interval of cycles in which the appliance must operate. The appliance is not allowed the operate outside its operating window.

Each appliance is responsible for requesting authorization to operate in each cycle, and they must reserve power before to start operating. Appliances cannot demand more power than needed to operate, even if there is energy left.

The attributes defined for each appliance are: power, the number of cycles that the appliance needs to operate per day, category, operation window and day shift. Each appliance is formalized using the following notation:

$$appliance(Pow, Cycles, Categ, Window[Start, End], DayShift) \tag{4.1}$$

Where *Pow* describes the energy required to operate in each cycle, *Cycles* is the number of cycles the appliance intends to operate per day, *Categ* defines the appliance category, *Window[Start, End]* informs which cycles the appliances may operate and *DayShift* inform which daily execution shift the appliance is scheduled to operate.

A washing machine, for instance, needs 600 watts to operate in one cycle, it needs 2 hours (4 cycles) to do the laundry, it is classified as a Wet appliance and the operating window has a size of 9 cycles, the washing machine operates between the cycles fourteen and twenty two, and this appliances is schedule to operate in the morning day shift. The notation below formalizes this example:

$$washing\_machine(600, 4, wet, window[14, 22], morning) \tag{4.2}$$

Figure 4.1 illustrates four possible operations to the washing machine inside its operating window and one invalid possibility. The green color indicates the cycles that the washing machine operates; the blue color indicates the washing machine operating window; and the red color indicates the cycles outside its operating window. So one option is the washing machine starts operating in the cycle 14 (the first cycle of its operating window) and keeps operating until the cycle 17 without interruptions. It can operate in nonconsecutive cycles as well, however the washing machine can not start after 19th cycle because if it does, it will not finish the laundry in the operating window.

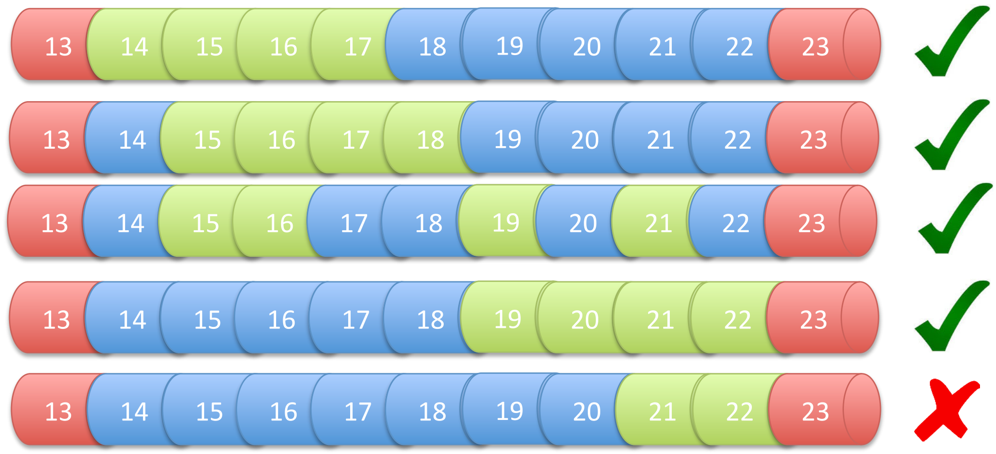

Figure 4.1 – Washing Machine Operation Window

Wet appliances usually work in well-defined periods of time. The operation that was not successfully completed on the same day can affect the next operation, e.g. a dish washer scheduled to operate in 3 cycles per day may occasionally be interrupted at the second cycle, as a result the dish washer cannot be scheduled to do the dishes in the next day because it must finish the previous operation.

Cold appliances work to satisfy certain configuration constraints, e.g., if a refrigerator is programmed to keep its temperature at 5 degrees Celsius, it should request power in order to maintain this temperature. For this type of device, power demand variation is associated to weather changes instead of user lifestyle, routine and preferences. For example, during summer the device might require a little less power, otherwise, during winter the device requires more power to keep the programmed temperature.

Temperature controllers typically demand power according users needs, e.g. the air conditioner should work to make the user comfortable. For example, summer temperatures in certain countries can easily reach 35 degrees Celsius and the user wants to get home and get cooler temperature, so the air conditioner should start working some time before the user arrives home.

Lifestyle appliances are strongly related to user routines, preferences and lifestyle, e.g. users who like cooking, users who are more focused on mobile technologies probably charge their mobile devices periodically. Assuming that this kind of users does not yield in their preferences, they will use the appliances from this category without taking into consideration the cost involved.

4.3 Household Profile

The focus of our work is to propose a control system model to manage the usage of power inside of a household, so it is necessary to define the elements that compose a household. In our model the power consumption is managed daily, it means that each day it is necessary to define the parameters of the control system. The household has a pre-defined quantity of power that can be consumed during a single day, the daily limit of power. As it is described in the section 4.2 the day it is divided in 48 cycles, each cycle has a limit as well used to avoid peaks of demand.

The elements that compose a household are: the daily limit of power, the cycle limit of power, the quantity of cycles per day, the daily execution shift and the list of appliances. Each day is formalized using the following notation:

$$day(DLimit, CLimit, NCycles, DShifts[Ds1[S, E], \ldots, DsN[S, E]], ListApp) \tag{4.3}$$

Where *DLimit* describes the amount of power available per day, *CLimit* is the amount of power that the appliances can consume per cycle. The control system must avoid the appliances consuming more power than the quantity defined in *DLimit* and *CLimit*. *NCycles* defines the number of cycles per day. *DShifts* informs the daily execution shifts, *Ds1* is the name of the first day execution shift and *[S,E]* informs in which cycle the shift starts and in which cycle it ends. *ListApp* defines the list of home appliances, this list is composed by a set of appliances as defined in the notation 4.1 The example below illustrates the notation from 4.3:

$$day(6000, 500, 48, DShifts[dawn[1, 12], morning[13, 24], \ldots, night[37, 48], ListApp) \tag{4.4}$$

For instance, the day is defined with a daily limit of 6000 watts and a cycle limit of 500 watts. In the model proposed in this work the number of cycles per day is fixed at 48 and the day execution shift follow de information from Table 4.3 The definitions from this chapter are used as base to define the smart home control system in Chapter 5.

5. SMART HOME CONTROL SYSTEM

We developed our smart home model through abstraction of virtual organization; and this organization was implemented using the JaCaMo framework. The organization with the roles, objectives and schemes are implemented at the Moise level. The environment artifacts that define the limit of power per day and limit of power per cycle are implemented at the CArtAgO level. Finally, the implementation of agents is done at the Jason level.

This chapter is divided in two main sections: Section 5.1 introduces how we control the power consumption, when the smart meter release energy and the rules the appliances must follow to demand and to consume power. Moreover, we show how the agents perceive time in the simulation and how they use this perception to decide if they can or cannot interact with the others. Section 5.2 introduces the power reserve protocol based in auction, this protocol defines how the appliances decide if they want to participate in the power auction, their bid strategy and the amount of power is auctioned in each auction.

The smart home control system can affect the user comfort. When a priority appliance is off the user comfort is affected. For instance, for a particular that user comfort is priority over saving energy, and this user define that the air conditioner must be on during all the time that there is somebody at home no matter how much power is spent, it means that the air conditioner is a priority appliance. When there is somebody at home and the air conditioner is off the user is unsatisfied.

We conducted three experiments aiming to evaluate how the smart home control system can affect the user comfort. In the first experiment we used what we called "the demand2Consume control system". Demand2Consume control system uses the power consumption control described in Section 5.1 and the results are described in Section 6.1. After that we evolved the control system and integrated the power reserve protocol based in an auction mechanism. The second control system integrates the controls described in Section 5.1 and Section 5.2; and the results are in Section 6.2.

To compare how effective the control system is we developed a third experiment confronting the power consumption of a household using the auction based control system against the power consumption of a household without any control system. We report this experiment in the section 6.3.

5.1 Power Consumption Control

The power consumption control defines that the appliances must ask for authorization before starting to consume power; and the smart meter must evaluate if the appliances power request can be attended. To accomplish this, the smart meter checks the power consumption restriction. The restriction checks the daily limit and the cycle limit by checking if there is power available to be consumed; and to avoid appliances from operating outside their operating window.

5.1.1 Organization Model

The virtual organization is defined in MOISE in terms of a scheme, which defines the power consumption; the set of roles, which define the organizational structure; and the goals, which correspond to tasks the roles has to achieve. The roles defined at this level are: the smart meter and appliances that are divided according to the categories described in Section 4.1. We defined one scheme to coordinate the power consumption. This scheme covers four goals; each goal has one associated mission. The first goal is to control peaks of demand, this goal is achieved through mission control demand, this mission can only be adopted by an agent playing the *SmartMeter* role. The three other goals are: demand energy, receive energy and execute in operation window; these three goals are achieved through the missions: demand energy, receive energy and execute in operation window; all agents playing an appliance role must commit to these three missions. At the top of the Figure 5.1 we have the MOISE Level, with the consumption scheme, the roles and goals.

The JASON level includes the agent implementation, in which the agents can assume the roles defined at MOISE level. The agents has a set of plans which are courses of actions triggered by events used to achieve the MOISE goals. Each agent can play just one role, however we allow some roles to be played by more than one agent; the air conditioner and the ceiling fan, for instance, can assume the role temperature controller. Each goal defined in the functional specification at MOISE level is met by plans implemented in the agents. Each agent represents an appliance, and their individual behavior takes into consideration the appliance types from Section 4.1. Consequently, we implemented a generic appliance-agent that includes initial beliefs common to all appliances, as well as a common plan library. At runtime, each appliance-agent commits to the same missions over time, depending on the appliance it controls. At the center of Figure 5.1 we have the Jason Level, with the agent implementations,

We implemented two CARTAGO artifacts to simulate the virtual environment: the first artifact controls the cycles, informing by perception to the agents, when the cycle starts, which is the current cycle and when a cycle finish. With these information the appliance can check if it is inside its operating window. Once the appliance is inside its operating window it can start negotiating energy with the smart meter. All agents in the simulation are aware of this artifact. The second CARTAGO artifact controls the energy load and the appliances consumption. Through this artifact, it is possible to check the limit of energy that is available to be consumed per day and the limit of consumption per cycle. This artifact is known only to the agent playing the *SmartMeter* role. At the bottom of Figure 5.1 we have the environment implemented using CARTAGO artifacts.

5.1.2 Demand2Consume Protocol

The Demand2Consume protocol is responsible for controlling the interaction between the smart meter and the appliances. The appliances must demand power to the smart meter before

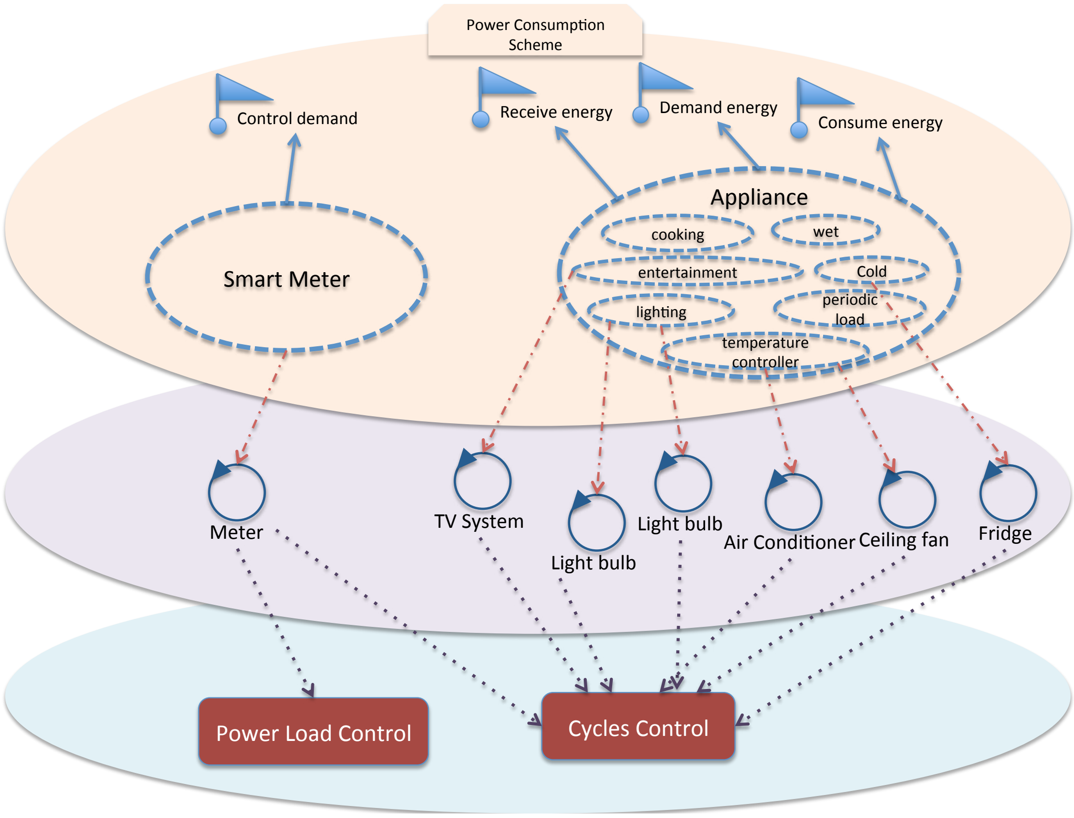

Figure 5.1 – Power Consumption scheme to the smart home model

start operating and the smart meter must evaluate whether the appliances can or cannot operate. This protocol was implemented using JASON plans. **Figure 5.2** illustrates how the smart meter and the appliances interact with each other. This figure has three layers: Environment, Appliance and Meter. The Environment layer is where the protocol begins; when the CARTAGO artifact responsible for controlling cycles update the cycles the environment *informs all agents that a new cycle has begun*; the Appliance layer shows when the appliances demand power, how the appliance defines how much power it intends to demand in each interaction; and the Meter layer shows in which circumstances the smart meter can release power.

The smart meter has the responsibility of releasing power to each appliance; monitoring the set of appliances to prevent them from operating outside of their operating window; controlling the daily limit of power and controlling the cycle limit of power (section 4.3); and prioritizing the appliances power demand. We have set a fixed sequence for appliances to demand power: first of all appliances that need to operate during all day should demand power; second the appliances scheduled to operate in a specific daily shift (e.g. morning, afternoon, night and dawn); and finally the appliances that can operate any time can demand power.

The appliances have to monitor their operating window, requesting the necessary power to the smart meter at the beginning of an operating window and in each cycle, and negotiate with the smart meter if they can operate in the current cycle or should wait until next one. Demand2Consume

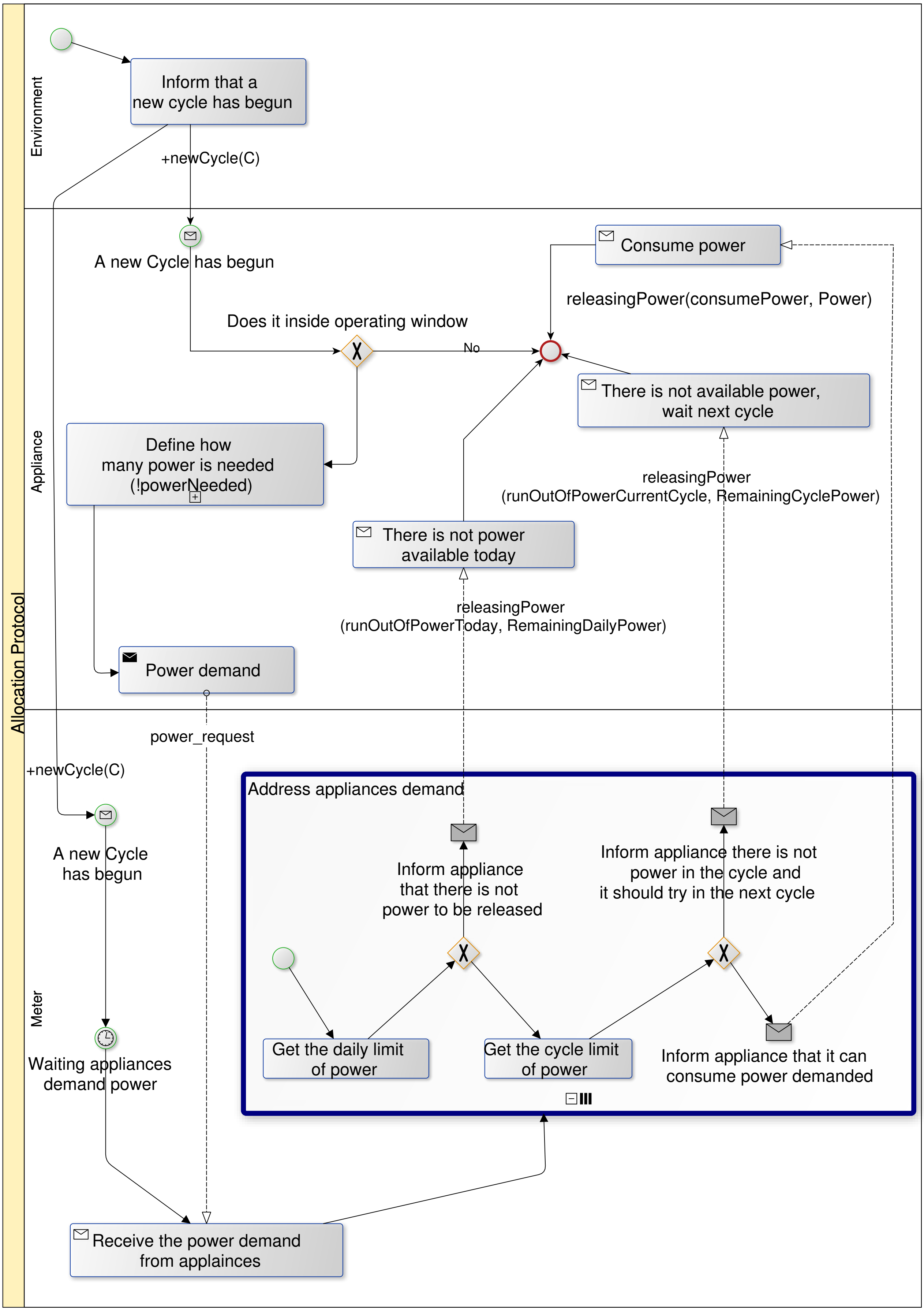

Figure 5.2 – Demand2Consume Protocol

begins when the smart meter and the appliances perceive from the environment that a new cycle has begun, then the smart meter updates the belief in its belief base that monitors the cycles i.e. (***+newCycle(C)***), and wait for the appliances to demand power. As long as the power requests come up, the smart meter addresses them all through the "Address appliances demand" plan. Meanwhile the appliances receive the information that a new cycle has begun by adding a new belief to their belief base. The appliances check if this cycle is inside its operating window, if that is the case, the appliance check how much power needs by using the plan ***!powerNeeded(Power)*** and then send a request to the smart meter informing its name, the daily shift it intends to operate and how much power it needs. The appliance accomplishes this by sending the literal ***power_request (Appliance, Shift, Power)*** to the smart meter, shown in Listing 2 line 9. Otherwise, if the current cycle is outside the appliance operating window, the appliance waits until the next cycle.

```
1  +!power_demand
2       :current_Cycle(Cycle) &
3       operating_window(Begin,End) & Begin <=Cycle & Cycle <=End &
4       lastCycleIdemandedPower(Last_cycle)& Cycle > Last_Cycle &
5       cycles_to_execute_remaining(R) & R>0
6  <-?.my_name(Me);
7       !powerNeeded(Me);
8       .send(smartMeter,tell,power_request(Me,Shift,Power));
9       .wait(10);
10      !!power_demanded.
```

Listing 2: power_demanded plan

The plan 'Check power needed' define how much power the appliance intends to demand. The amount of power that each appliance can demand is related to the category of the appliance, in this model if an appliance needs to operate in all operating window without interruption it means that this appliance can demand all necessary power. In what follows, we describe two examples of operation. In the first example a refrigerator that must not run out of power and its operating window beginning at the first cycle and finishing at the last cycle, as a result this appliance can demand the power necessary to operate in all cycles. In the second example a wet appliance such as a washing machine with an operating windows of 4 cycles, in this case the washing machine does not need to operate continuously, as a result this appliance demands the power necessary to operate in one cycle. The literal that represents this plan is: ***!powerNeeded(power)***.

The 'Address appliances demand' plan begins when the smart meter receives a power request from an appliance, as mentioned before each power request is addressed individually. The smart meter check how much power remains available to be released in the current day, if the quantity of power remaining is less than the amount demanded by the appliance, the smart meter informs to the appliance that it is not possible to provide power because the daily limit has been reached. In that moment the appliance knows that it is useless to keep demanding power in the current day, as a result the appliance can stop demanding power and must wait until next day. The smart meter sends the literal ***releasingPower(runOutOfPowerToday, RemainingDailyPower)*** to the appliance that has requested power informing that there is not power available.

Otherwise, if there is enough power available in the daily limit the smart meter checks the cycle limit, if there is not enough power or if the cycle limit has been reached, the smart meter must inform the appliance that any power will be released because the cycle limit can not be violated and the appliance needs to wait until the next cycle to try again. The smart meter sends tot he requesting appliance the literal ***releasingPower (runOutOfPowerCurrentCycle, RemainingCyclePower)*** informing that it is not possible release more power in the current cycle but the next cycle has power available.

After that the smart meter informs the requesting appliance if it can or cannot consume the power demanded. If there is power in the daily reserve and the cycle limit has not been reached the smart meter release power to the requesting appliance by sending the literal ***releasingPower (consumePower, PowerDemanded)***

Finally, if the smart meter concludes that the appliance can be released power, the smart meter informs the appliance that is releasing a specific quantity of power. The agent accomplishes this by sending the literal: ***releasingPower(consumePower, PowerDemanded)***.

After the appliance receives the authorization to consume power from the smart meter, this appliance must check if it is still inside its operating window because sometimes the appliance demands power in one cycle but receives the answer in the next cycle.

When the appliances perceive from the environment that a new cycle has begun and add belief ***newCycle(C)*** in their belief base the appliances execute the power demand plan. Power demand plan checks if the current cycle is inside of the appliance's operating window, if the appliance has not demanded power in the current cycle yet and if the appliance still have intention to operate; if these three checks are true the appliance sends a power request to the smart meter. After that, the appliance waits for a while and try to perform the same plan again. **Listing 2** shows this plan.

```
@b1[atomic]
+power_request(Appliance, Shift, Demand)
        :daily_load(RemainingDailyPower) & RemainingDailyPower < Demand
        <-.send(Appliance, tell, releasingPower(runOutOfPowerToday,
           RemainingDailyPower).

@b2[atomic]
+power_request(Appliance, Shift, Demand)
        :cycle_load(RemainingCyclePower) & RemainingCyclePower < Demand
        <-.send(Appliance, tell, releasingPower(runOutOfPowerCurrentCycle,
           RemainingCyclePower).

@b3[atomic]
+power_request(Appliance, Shift, Demand)
        :daily_load(Power_remaining)  & Power_remaining  >= Demand &
        cycle_load(PCycle_remaining) & PCycle_remaining >= Demand &
        current_cycle(Cycle)
        <-.send(Appliance, tell, releasingPower(consumePower, Demand).
```

Listing 3: Smart meter power_request plan

The smart meter addresses the appliances requests through the plan ***power_request***. First, the smart meter must inform that the daily limit run out of power if there is not power available (Listing 3 line 3). If there is power available the smart meter checks the cycle limit (Listing 3 line 8); and if the cycle limit was reached the smart meter must inform the appliance that it is not possible to get power in the current cycle. However, if there is enough power to be released, the smart meter answer the power request releasing the power demanded. This plan must be atomic to prevent the smart meter to attend more than one request simultaneously and exceeds the limit of power.

```
+releasingPower(consumePower, Power):
  Power <=0 &
  demand_per_cycle(P) & Power >= P &
  current_cycle(Cycle) &
  operating_window(Begin,End) & Begin <= Cycle & Cycle <= End &
  cycles_to_execute_remaining(R) & R > 0
<--releasingPower(consumePower, Power);
  -cycles_to_execute_remaining(R);
  +cycles_to_execute_remaining(R - 1);
  ?.my_name(Me);
  update_LoadConsumed(Me, P, Power - P, R-1).
```

Listing 4: releasingPower plan from Appliance

When the appliances receives authorization to consume power the plan ***releasingPower(consumePower, Power)*** handles the power consumption, in which variable *Power* informs how much power the smart meter released to the appliance. Fist of all, the appliance checks if the amount of power received is enough to operate, if it is receiving power inside of its operating window and if it still has cycles to operate; when these checks are true the appliance removes the information sent by the smart meter from the belief base, updates the quantity of cycles to operate remaining and updates the consuming information using an internal action. **Listing 4** shows how the appliance handles the power consumption.

5.2 Power Reserve Auction-based Protocol

This subsection introduces a new control to our smart home model. It is important that the appliances organize themselves predicting how much power they intend to consume and reserving this power before starting to operate. As a result to know the power consuming intention helps the smart meter controls the daily demand.

This protocol defines that the appliances must participate in auctions to reserve the power to operate. The auctions happen in the beginning of each daily shift (Table 4.3), however the power reserve does not ensure that the appliances will operate, they still need to ask for authorization.

5.2.1 Organization Model

The roles defined at the MOISE level are: auctioneer, bidder (that are divided according the profiles described in Section 5.2.2), smart meter and appliances (that are divided according to the categories described in Section 4.1). The auctioneer is responsible for performing the auctions and only agents playing the bidder role are allowed to participate in the auctions. Smart meter is the role responsible for controlling the power consumption, and an appliance is the role responsible for negotiating and consuming power.

The auction scheme organizes the auction dynamic. Table 5.1 describes the missions covered by the auction scheme and informs which role must commit with each mission.

Table 5.1 – Auction Scheme

Mission	**Description**	**Role**
Return reserve of power	Before entering in a new cycle of auctions the agent playing the bidder role must return the unused energy	Bidder
Update reserve of power	Before performing the round of auctions the agent playing the role auctioneer must increase the reserve of power with all unused power released by the bidders	Auctioneer
Participate in the auction	The agent sign up in the next auctions round if it needs power in the next daily shift	Bidder
Perform auction	The auctioneer performs the auctions	Auctioneer

The JASON level includes the agent implementation. Each agent can play two roles: one role from the power consumption scheme and other role from the auction scheme. The fridge, for instance, can assume the role of cold appliance because it wants to consume power in the power consumption scheme and can assume the role of bidder to participate in auctions in the auction scheme. Each goal defined in the functional specification at MOISE level is met by plans implemented in the agents.

Section 5.1 describes the cycles control and power control artifacts, now we add a third artifact to control the bids in the auctions. This third artifact informs who is the winner of each auction. The agent playing as auctioneer must create the auction, open the auction to receive bids and close the auction. All agents signed to participate in the auction can bid. This artifact is known to all agents playing as bidder and auctioneer roles.

Figure 5.3 illustrates the auction scheme: at the top we have the MOISE Level, with the roles and goals. At the center we have the agents at the JASON level, and at the bottom we have the CARTAGO artifacts.

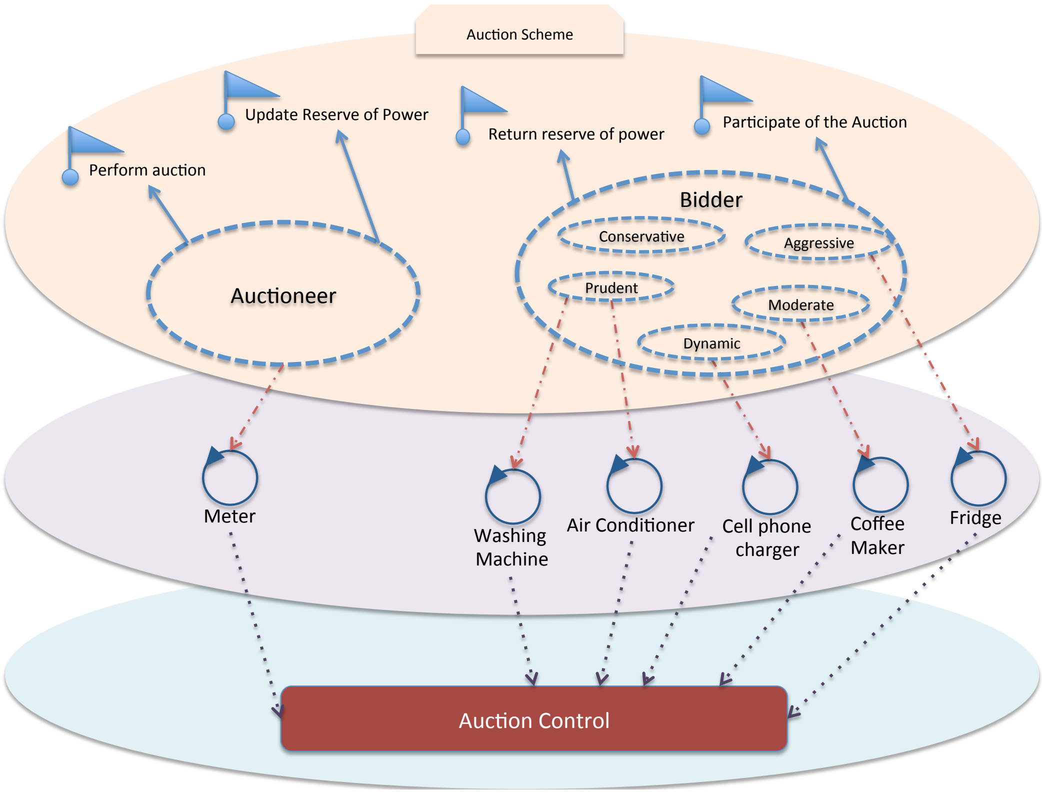

Figure 5.3 – Auction scheme to the smart home model

5.2.2 Auction Dynamic

In a conventional home the appliances are plugged in the electrical circuit and since the electrical circuit is energized they begin to consume power in the moment they are turned on, there is no control to manage the consumption. In the model proposed in this work the power consuming are coordinated, it means that the appliances must get power before start operating. The power reserve is organized through ascending price auction.

In this type of auction participants bid openly against one another, with each subsequent bid required to be higher than the previous bid. An auctioneer may announce prices, bidders may call out their bids themselves. The auction ends when no participant is willing to bid further, at which point the highest bidder pays their bid. The auction is organized in lots, an item or set of items for sale in an auction. The auctioneer sets a minimum amount to each lot before the auction begins by which the next bid must exceed the current highest bid [31].

In this model the lots have the same amount of power, and the appliances can participate in the auctions using a virtual credit. In this model all appliances start with the same quantity of virtual credits however the appliances can assume different strategies during the auctions. Five different strategies are defined in this model: conservative, prudent, moderate, aggressive and dynamic.

- **Conservative**: The bidder following the conservative strategy offers always the same price. The appliances that do not have priority to operate may choose this strategy.
- **Prudent**: The prudent strategy is to bidder that takes a lot of time before to do a new bid and they increase their bids constantly 10 by 10 virtual credits. The bidder that choose this strategy in average bids 2 to 3 times per auction.
- **Moderate**: The moderate strategy increase the bid constantly too, however 30 by 30 virtual credits and bidders that choose this strategy perform bids faster than the prudent bidders but slower than the aggressive bidders. This strategy allows the appliance takes twice more bids than an appliances that chose the prudent strategy.
- **Aggressive**:The aggressive bidders do not think too long before to do a new bid and they increase their bids 50 by 50 virtual credits, so the aggressive bidders perform bids faster than all other bidders. The aggressive bidder may perform in average 10 bids per auction.
- **Dynamic**: The last strategy is to dynamic bidders. A dynamic bidder perform bids faster than moderate bidders but slower than aggressive bidders. These bidders increase the bid randomly, and they are very difficult to anticipate.

Table 5.2 – Example of bids to the different profiles - The aggressive bidder is the winner

Time	Conservative	Prudent	Moderate	Aggressive	Dynamic
T1			80		
T2	90				
T3				140	
T4					152
T5				202	
T6			232		
T7					255
T8				305	
T9		315			
T10				365	
T11					350
T12			380		
T13		390			
T14				440	
T15					455
T16				505	
T17			535		
T18				585	
T19					605
T20				655	
T21		665			
T22			695		
T23				745	

Table 5.2 introduces an auction section with 5 bidders each one with following a different strategy. The initial value to the lot in this auction is 50 virtual credits, so the following bids must be higher than this. The conservative bitter intends to pay only 90 virtual credits, as a result it stops and gets out of the auction after the first bid. A prudent bidder thinks a lot over before call out a new bid, as a result it perform just few bids in an auction. The moderate and the dynamic bidders do not wait to long between the bids. The aggressive bidder reacts very fast to the changes during the auction, this bidder has higher chances to win the auction.

5.3 Auction Allocation Protocol

The auctioneer has the responsibility of informing all potential bidder when a new auction begins; when the auction finishes; informs who is the winner to each auction; and manages the reserve of power. Once a bidder decides to participate in an auction it should follow its strategy to perform bids according strategy defined in section 5.2.2.

The auctions are performed 4 times per day, in the beginning of each daily shift (Table 4.3). The auction allocation protocol begins when the agents perceive from the environment that a new daily shift has begun. First, the auctioneer gets the amount of auctions that can be performed based in the amount of power that is available and in the amount of power will be disputed per auction, if there is enough power to be auctioned it will create and start disputes. The chapter 6 describes how we configure this parameters to validate our model.

In the meantime, the bidders check if they have the intention to operate in the next daily shift. If a bidder has the intention to operate in the next daily shift, it must reserve power, consequently it will participate in the auctions.

The auctioneer opens one auction per time and bids can be performed while the auction is opened. The auctions have a predetermined time to be open, when this time ends the auctioneer closes the auction, decreases the power reserve and send the power to the auction winner. The cycle of actions finishes when the auctioneer performs 5 rounds without winner, that means that all agents have enough power to operate in the next daily shift or means that the bidders do not have enough credits to perform new bids.

When the auctioneer informs the bidders that a new auction has opened the bidders begin to bid. If the bidder agent is not the current winner and its strategy allows it to make new bids, the agent sends a higher bid. Then the auction finishes if the bidder is the winner it receives a quantity of power that must be added in its power reserve.

The auctioneer creates a new CArtAgO artifact to each new auction; and after that the agent informs all bidders that there is a new auction (e.g.,***!tell_Appliances(discover_art(ArtName))*** is a plan in which *ArtName* is the name of the new auction artifact). The bidder that has intention to participate in the auction must find the new artifact and then focus on it. The interaction between the auctioneer and the bidders is illustrated by Figure 5.4. This Figure shows when a new cycle of

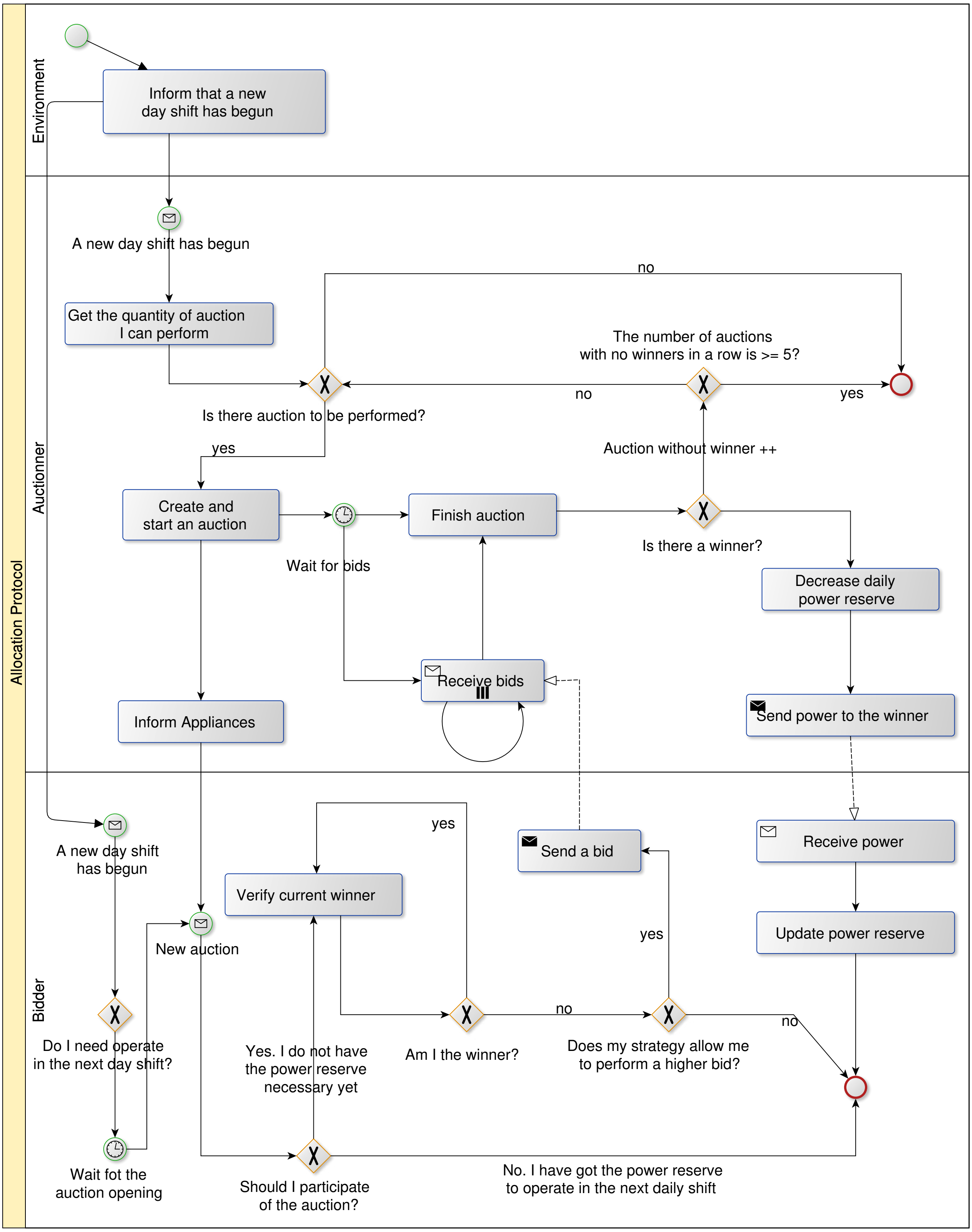

Figure 5.4 – Auction Allocation Protocol

auction must begin; the Auctioneer layer shows the auctioneer deciding how many auctions it can perform; and in the Bidder layer how the bidder decides whether to participate in an auction.

As described in Table 5.1 the auction scheme has 4 missions: firstly the bidders must return the reserve of power they got in the preview cycle of auctions but did not use; secondly the auctioneer must update the reserve of power with the power the bidders have returned; after that the bidders sign up to next cycle of auctions; and finally the auctioneer opens the dispute for power.

```
+!return_reserve_of_power :power_reserve(Power) & Power > 0
        <-.println("I have Power to return.");
        .send(auctioneer, tell, powerToBeReturned(Power));
        -power_reserve(Power);
        +power_reserve(0).
+!return_reserve_of_power <-.println("I do not have Power to return.").
```

Listing 5: Return reserve of power

If the agent has power left it must send the unused power to the auctioneer using the literal ***powerToBeReturned(Power)*** in which *Power* informs how much power the bidder is returning. After that the agent updates its power reserve. **Listing 5** illustrates the bidder using the ***return_reserve_of_power*** plan to return the unused power.

The auctioneer handles the **update reserve of power** mission defined in the auction scheme at Moise organization through the ***update_reserve_of_power*** plan. The auctioneer gets all the power sent by the bidders and increases the daily power reserve by calling the CArtAgO artifact responsible for controlling the power load. **Listing 6** illustrates how the auctioneer handles the **update reserve of power** mission.

```
+!update_reserve_of_power : powerToBeReturned(_)
        <-.println("There is Power to be returned.");
        ?current_cycle(Cycle);
        for ( powerToBeReturned(Power)[App] ) {
                increase_daily_power_reserve(Cycle, Power);
                -powerToBeReturned(Power)[App];
        }.
+!update_reserve_of_power<-.println("There is no Power to be returned.").
```

Listing 6: Update reserve of power

After the auctioneer updates the power reserve with the unused power sent by the bidders, the bidders check their intention to operate in the next daily shift by comparing their the believe **day_shift(MyShift)** with the perception **next_Shift(Shift_Next)**, in which *MyShift* is the daily shift that the appliance intends to operate and *Shift_Nextt* informs the next daily shift. Then the agents checks if they have enough power in their power reserve or should participate the next auction to try to get power. The **Listing 7** describes the check_participation_in_the_auction plan; and **Listing 8** illustrates how the agents tests whether they has enough reserve of power to operate or not.

```
+!check_participation_in_the_auction
        :day_shift(MyShift) & next_Shift(Shift_Next) &
        ( .substring(MyShift, Shift_Next) | day_shift(all) | day_shift(any)) &
        should_participate_next_auction(Result) & Result = true
        <--bid(_);
        +bid(true);
        .println("I will participate of the Auction").

+!check_participation_in_the_auction
        <--bid(_);
        +bid(false);
        .println("I will not participate of the Auction").
```

Listing 7: Verify participation in the auction plan

Perform auction is the last mission that needs to be accomplish by the auctioneer. To do that the auctioneer checks the number of auctions that an be performed in the next daily shift (e.g., ***number_of_actions(N_actions)*** in which *N_actions* is the maximum number of auctions that cans to be performed according the scenarios restrictions described in section 6.2.1); and starts performing the auctions.

Each bidder can assume just one strategy, it is now accepted a bidder with multiple strategies. **Listing 9** shows the five strategies that the bidders can assume. Line 1 introduces the conservative strategy, offering a fixed price if the bidder is not the winner and the fixed price is higher than the current price. Lines 8, 16, 24 show the prudent, moderate and aggressive strategies respectively. Before to offer a new bid the bidder use the plan ***should_participate_next_auction*** to check if should continue participating in the auction or if it has enough power to operate in the next daily shift (Listing 8) .

```
should_participate_next_auction(Result):-
        power_reserve(Reserve) &
        power_to_operate_in_this_shift(Need) &
        Need > Reserve & Result = true.

should_participate_next_auction(Result):-
        power_reserve(Reserve) &
        power_to_operate_in_this_shift(Need) &
        Need <= Reserve & Result = false.
```

Listing 8: Auction participation

Assuming that a auction would be open for one second, line 13 shows that a prudent bidders think a lot before to do a new bid, in addition line 21 shows that a moderate bidders think a while before to do a new bid and finally line 29 shows that an aggressive bidders do not thing so long before to do a new bid.

The power consumption control can help the household users to save power; once the users profile is defined the control system works to keep the power consumption limits. The control system respects the user preferences; if keeping comfort it is more important to the user than saving

```
+currentBid(V)[artifact_id(Art)]
        :not i_am_winning(Art)  &
        bidder_strategy(fixed_price) &
        should_participate_next_auction(Result) & Result = true &
        my_price(P) & P > V
   <- bid( P )[artifact_id(Art)].

+currentBid(V)[artifact_id(Art)]
        :not i_am_winning(Art) &
        bidder_strategy(prudent) &
        should_participate_next_auction(Result) & Result = true &
        my_price(P) & P > V
   <- .wait(math.random(250)+500);
       bid( math.min(V+10,P) )[ artifact_id(Art) ].

+currentBid(V)[artifact_id(Art)]
        : not i_am_winning(Art) &
        bidder_strategy(moderate) &
        should_participate_next_auction(Result) & Result = true &
        my_price(P) & P > V
   <- .wait(math.random(250)+250);
        bid( math.min(V+30,P) )[ artifact_id(Art) ].

+currentBid(V)[artifact_id(Art)]
        : not i_am_winning(Art) &
        bidder_strategy(aggressive) &
        should_participate_next_auction(Result) & Result = true &
        my_price(P) & P > V
   <- .wait(math.random(250)+100);
        bid( math.min(V+50,P) )[ artifact_id(Art) ].

+currentBid(V)[artifact_id(Art)]
        : not i_am_winning(Art) &
        bidder_strategy(dynamic) &
        should_participate_next_auction(Result) & Result = true &
        my_price(P) & P > V
   <- .wait(math.random(250)+200);
        Bid = V + math.floor(math.random(20));
        bid( math.min(Bid,P) )[ artifact_id(Art) ].
```

Listing 9: Bids Strategy

power the limit of power that can be consumed per day and the limit of power available per cycle should be high allowing the users turn on as many appliances as they want. However if the household is configured to save power stepping aside the users comfort, in this case it is possible to see the appliances failing to operate.

Since the power consumption control strike the balance between user comfort and power saving; the power reserve protocol based in auction helps to maximize the way the power is allocated among the appliances. During auctions appliances that follow more aggressive strategies take advantage over the appliances that follow less aggressive strategies.

After we concluded the description of the model we present in the chapter 6 the experiments used to validate the model.

6. EXPERIMENTS AND EVALUATION

In this chapter we show how we evaluate the model from chapter 5. We are monitoring two moments: the peaks of demand, when the appliances have intention to operate and demand power to the smart meter; and the peaks of consumption; when the appliances effectively consume the power received. In a household without any control system the appliances can operate without restriction, it may result in peaks of consumption. These peaks of consumption can cause an interruption in the electrical circuit. The results evaluated in this chapter shows that our model can coordinate the household power consumption avoiding peaks of consumptions.

The first section of this chapter shows how we evaluated the Demand2Consume Protocol. In the second section we explain how we evaluated the Power Reserve Protocol Based in Auction and in the last section we compare our model with a stochastic smart home simulator.

6.1 Evaluation: Demand2Consume Protocol

In this section we describe the setup used in our experiments to evaluate the model described in Section 5.1. This set up includes the environment used in the simulations which contains the daily shift configuration and the appliances profile described in Section 4.2.

6.1.1 Experiment Setup

Based on average household consumption in the south of Brazil [9] (the data which was described in chapter 5.1), we determined that a household consumes, on average, 186 kwh per month during summer time or 6.2 kwh per day. For our simulation we divide each day into 30-minute long time slots, and call these slots: *cycles*. Thus, each day has 48 cycles, the first cycle starts at 0:00 AM and ends at 00:29 AM.

The group of appliances used in the simulation is described in Table 6.1. For each appliance we have: the power required for operation, the number of cycles they intend to operate per day, the category and the operating window.

Three different scenarios were considered in order to compare the results:

- The first scenario focuses on the **average consumption** throughout the day, we assumed that the peak of demand allowed in each cycle for a household where 3 people live together [9] should be 10% of the daily load.
- The second scenario prioritizes **energy saving** and focuses on the user economy and the peak of demand per cycle allowed is 3.33% of the daily load (one third of the peak allowed in the

Table 6.1 – Appliances used in the simulation

Appliance	Power (W)	Cicles per day	Daily Demand	Category	Operating Window
Bedroom Air conditioner	1000	5	1650	Temperature Controller	37 to 44
Living room Air conditioner	1000	2	660	Temperature Controller	13 to 16
Washing machine	600	0.5	150	Wet	1 to 48
Coffee maker	500	0.2	50	Cooking	13 to 14
Toaster	700	0.2	70	Cooking	13 to 14
Microwave	1000	0.5	250	Cooking	41 to 45
Refrigerator	50	48	1200	Cold	1 to 48
Television System	400	4	800	Entertainment	38 to 45
Computer	200	3	300	Entertainment	39 to 44
Cellphone charger	6	4	12	Periodic Load	1 to 13
NoteBook computer charger	60	4	120	Periodic Load	40 to 48
Hair dryer	600	0.5	150	Personal Care	40 to 46
Clothes Iron	800	1	400	Miscellaneous	25 to 32
Vacuum	800	0.5	200	Miscellaneous	26 to 33
Celling Fan	120	6	360	Temperature Controller	41 to 48
2 Living room Fluorescent light bulbs	40	4	80	Lighting	37 to 42
Bathroom Fluorescent light bulbs	20	4	40	Lighting	40 to 44
Kitchen Fluorescent light bulbs	20	4	40	Lighting	37 to 42
Bedroom Fluorescent light bulbs	20	4	40	Lighting	40 to 48
2 Living room LED bulbs	12	6	36	Lighting	37 to 42
1 Living room LED bulb	6	6	18	Lighting	37 to 42
3 Dining room LED bulbs	18	2	18	Lighting	39 to 43

first scenario). In this scenario the user comfort is disregarded and some appliances may fail to operate because the competition for energy is high.

- In the third scenario the user **comfort** is given top priority, so this scenario allows a peak of demand per cycle of 60% of the daily load. The appliances operating window are distributed in the 48 cycles because we assume that the group of appliances defined here does not operate together, however the peak of demand defined in this scenario allows all appliances to operate at the same time.

6.1.2 Results

To empirically evaluate these scenarios we simulated each of them 100 times. We extracted the results and compared the total power demanded in each cycle and the total power consumed in each cycle.

The refrigerator must operate in all cycles, this appliance is allowed to demand all necessary power in the first cycle resulting in a virtual reserve of power for the refrigerator. This virtual power reserve causes a peak of demand in the first cycle. Figure 6.1 shows a chart of the power demanded in each of three scenarios. The refrigerator demands all the necessary power in the first cycle but receives power during the first cycle in almost 95% of the cases and received in the next cycle in 2% of the cases.

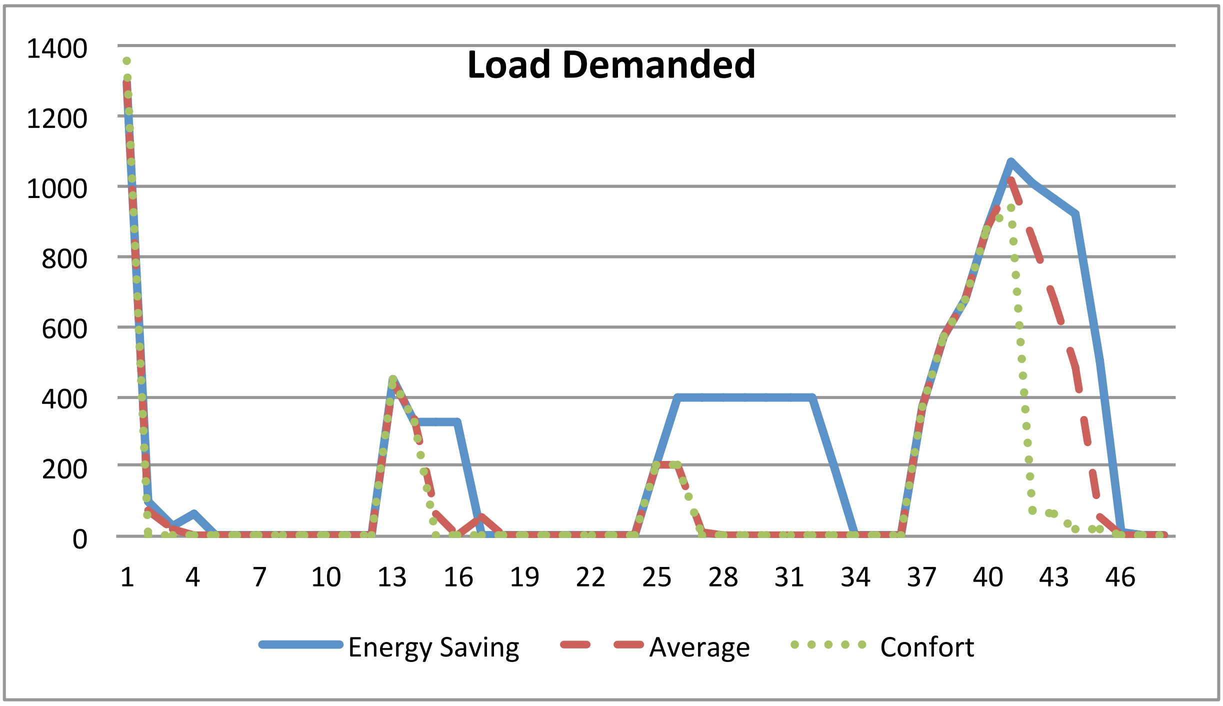

Figure 6.1 – Power demanded in each scenario

The operating window between 13th and 16th cycles; 25th and 33rd cycles; and 37th and 45th cycles exemplify how the Demand2Consume Protocol deals with the peaks of demand and avoids peaks of consumptions.

In the operating window between cycles 13 and 16 in the energy saving scenario, where the air conditioner, the coffee maker and the toaster intend to operate. As the air conditioner demands more energy than the cycle limit, it creates a peak of demand and fails to operate in all cycles of its operating window. Otherwise, the toaster and the coffee maker intend to operate for just few minutes, as a result they receive the energy necessary to operate. In the average and comfort scenarios there is a peak in the 13th cycle but it does not violate the cycle limit, all three appliances are able to operate within their operating window.

Likewise, the vacuum and the clothes iron are scheduled to operate between cycles 25 and 33. Both of them need 200 watts to operate and they should dispute power with the refrigerator. However the refrigerator consumes 25 watts per cycle and it has a virtual reserve of energy. The cycle limit in the energy saving is 205 watts, as a result the vacuum and the clothes iron cannot operate in this scenario. Besides, in the other two scenarios the vacuum and the clothes iron are allowed to operate. Figure 6.1 illustrates the peak of demand in the energy saving scenario between the cycles 25 and 33; and Figure 6.2 shows that the vacuum and the clothes iron consume power in the average and comfort scenarios.

Further the appliances that intend to operate between cycles 37 and 45 show an interesting behavior for comparing the three scenarios. The air conditioner is programed to begin over the 37th cycle, the television system operating window begins at 38th cycle, the computer is set to operate in three cycles between 39th and 44th cycles and the hair dryer has intention to operate just fifteen minutes (0.5 cycle) between 40th and 46th cycles. Together these four appliances need more than 900 watts to operate. This causes a peak of demand between cycles 38 and 44. However the appliances behave differently in each of the three scenarios, as described below.

In the energy saving scenario the cycle limit is 205 and the air conditioner and television system demand 330 watts and 210 watts per cycle respectively; it means that they demand more power than the limit allowed per cycle. The computer and the hair dryer have permission to operate in this scenario because their demand 100 and 150 watts respectively. Although, they can not operate in the same cycle because the sum of their demand it is higher than the cycle limit, thus in cycles that the hair dryer and the computer demand energy together sometimes one receives energy and the other does not and sometimes the opposite.

Meanwhile in the average scenario the behaviors of the air conditioner, the television system and the computer are quite different. The cycle limit allows just two of them to receive energy per cycle resulting that the power usage is distributed along the cycles, avoiding peaks of demand in cycles that these three appliances demand power together (between cycles 39 and 44).

Finally, in the comfort scenario we can see that the air conditioner, the television system, the computer and the hair dryer get energy in the first cycles of their operating window, because the cycle limit is higher than their demand. As a result there is a significant peak of demand and peak of consumption beginning in cycle 36 and reaching its top in the 40th cycle.

These three example shows how the control system affect the appliances intention to operate by releasing as much power as the cycle limit allows. Figure 6.1 illustrates that the peak of demand exceeds 1000 watts in 41st cycle, however Figure 6.2 illustrates that the power consumption is different in each scenario. And in the comfort scenario the peak of demand it is similar to the peak of consumption. We can conclude that the energy saving scenario strongly affects the user comfort because many appliances do not receive power and consequently fail to operate. On the other hand, in the comfort scenario the peak of demand it is similar to the peak of consumption because any appliance fail to operate. And the average consumption scenario balance the user comfort and the energy saving because the consumption is distributed and there is no peak of consumption.

After cycle 37 the light system begins to operate, as the sum of all lights is very low in all three scenarios it is not possible to observe any kind of variation in the light appliances. It is necessary to modify the light appliances profile to observe the behavior of the lights being affected in different scenarios.

These simulations shows that it is to possible affect the use of power in a household using the demand2Consume control system, because in a house without a control system the appliances

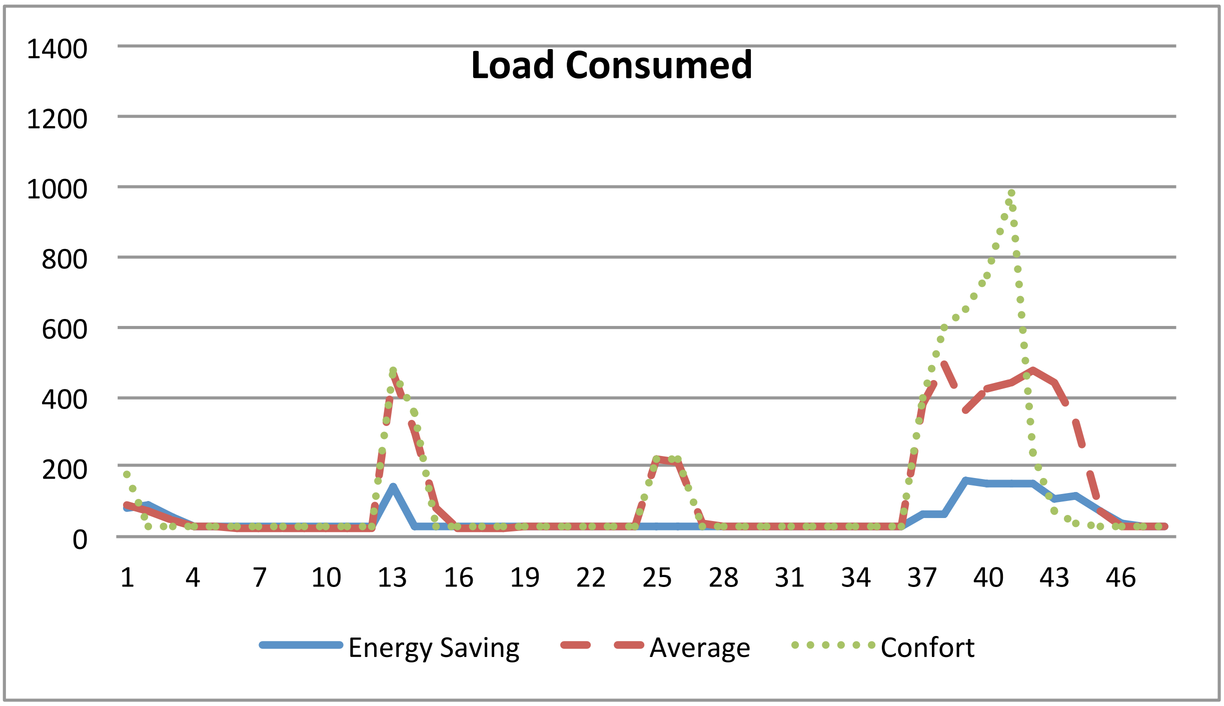

Figure 6.2 – Power consumed in each scenario

can operate without restriction, but demand2Consume control system avoids the appliances operate without smart meter authorization. The smart meter has a very important role by monitoring the electricity usage and ensuring that the daily limit of power and the cycle limit of power are not infringed. The household users must know their routine to configure the control system to have the expected balance between comfort and power saving.

6.2 Evaluation: Auction Power Reserve Protocol

In this section we describe the setup used in our experiments to evaluate the model that integrates the Demand2Consume protocol described in section 5.1 and the power reserve protocol described in section 5.2. Similar to the previous model, the appliances must demand power to the smart meter and the smart meter decides if the appliances are able to consume power, so the power consumption scheme illustrated by figure 5.1 is still considered.

Demand2Consume protocol is responsible for coordinating the appliances to avoid peak of consumption, but this protocol does not prioritize the appliances according the users will. The sequence for appliances to demand power described in Section 5.1 is not enough to satisfy the user priorities. The integration between the Demand2Consume protocol and Power Reserve Auction-based Protocol allows the power system to avoid peak of consumptions and prioritize the appliances that should be given preference to operate.

6.2.1 Experiment Setup

To evaluate the auction based control system model we considered the same group of appliances presented in Table 6.1. Moreover, as the appliances must dispute for power reserve we define the bids strategy to each device. Table 6.2 shows the strategy that each appliance must follow according the auction dynamic defined in section 5.2.2; and also shows how much virtual credits each appliance has to spend in their bids.

In this model the appliances that follow the fixed price strategy have their amount of virtual credits predefined, all other appliances have the same amount of credits. Before each daily shift the auctioneer prepares and performs the auctions cycles. This model still considers the three scenarios described in section 6.1.1: average consumption; energy saving and comfort. The amount of power available to be auctioned is related with each scenario.

The comfort scenario allows the auctioneer to create as many lots as the amount of power available. For instance, in a household arranged to consume 6.2 kw per day and each lot offers 50 watts of power; so in the first cycle of auctions the auctioneer can auction 124 lots. Supposing the bidders disputed and received 2000 watts in the first cycle of auctions then in the second cycle the auctioneer can create no more than 84 lots because it has 4200 watts to be auctioned. In the average consumption scenario the limit of power that can be auctioned by daily shift is half of the daily limit. If the daily limit is 6200 watts and each lot has 50 watts of power; as a result the auctioneer can not perform more than 62 auctions because the limit of power per cycle is 3200 watts. Lastly in the energy saving scenario the amount of power available to be auctioned per cycle of auction is one third of the daily limit; that means 2067 watts.

Each cycle of auction is described using the following notation:

$$auctions(AuctionNumber, Power, Value) \tag{6.1}$$

Where *AuctionNumber* describes the maximum number of auctions per cycle of auction, *Power* is the amount of power will be auctioned and *Value* defines the initial value for the bids. In our simulations we defined that the auctions offers 30 watts per round and the initial value is fixed in 50 virtual credits.

6.2.2 Results

To empirically evaluate these scenarios we simulated each of them 100 times. We extracted the results and compared the power demanded, the power consumed and the usage of the reserve of power.

In this model we defined that the appliances must reserve only the power to operate in the next daily shift; they are not allowed to reserve more power than the power necessary to operate in

Table 6.2 – Appliances strategy

Appliance	**Strategy**	**Virtual Credits**
Living room Air conditioner	Prudent	10000
Bedroom Air conditioner	Moderate	10000
Washing machine	Prudent	10000
Coffee maker	Moderate	10000
Toaster	Dynamic	10000
Microwave	Aggressive	10000
Refrigerator	Aggressive	10000
Television System	Aggressive	10000
Computer	Fixed Price	7000
Cellphone charger	Fixed Price	3000
NoteBook computer charger	Fixed Price	500
Hair drier	Moderate	10000
Clothes Iron	Dynamic	10000
Vacuum	Dynamic	10000
Celling Fan	Aggressive	10000
2 Living room Fluorescent light bulbs	Prudent	10000
Bathroom Fluorescent light bulbs	Prudent	10000
Kitchen Fluorescent light bulbs	Moderate	10000
Bedroom Fluorescent light bulbs	Prudent	10000
2 Living room LED bulbs	Aggressive	10000
1 Living room LED bulb	Prudent	10000
3 Dining room LED bulbs	Fixed Price	500

one daily shift. The auctions happen in the beginning of each daily shift, before to begin the 1^{st}, 12^{th}, 24^{th} and 36^{th} cycles. As described in section 6.2, the limits of power available per cycle of auctions: 2067 watts in the energy saving scenario; 3100 watts in the average scenario; and 6200 watts in the comfort scenario.

The column *Cycles per day* in table 6.1 describes how many cycles the appliances intend to operate per day. The highest concentration of appliances intending to operate concentrates in the 4^{th} daily shift, as illustrated by Figure 6.3. To accomplish these intentions of operation the appliances should reserve around of 4000 watts in the last cycle of auctions. In the comfort scenario the appliances get all they need because the limit is higher; in average scenario some appliances are unable to get power because the limit is lower than in the comfort scenario; and in the energy saving scenario the appliances get only half of the necessary power to operate, consequently many appliances fail to operate because they do not have reserve of power.

Excluding the fourth cycle in the energy saving scenario the appliances get in the auctions the power necessary to operate. In the first daily shift between 1^{st} and 12^{th} cycles, the appliances spend all the reserve of power however in the second and third daily shift they cannot because the cycle limit does not allow them to use the reserve of power. As a result, in the end of each daily shift the appliances must return the unused power to the auctioneer. Before to start the cycles of auctions in the beginning of 24^{th} cycles the appliances return in average 700 watts; before the last

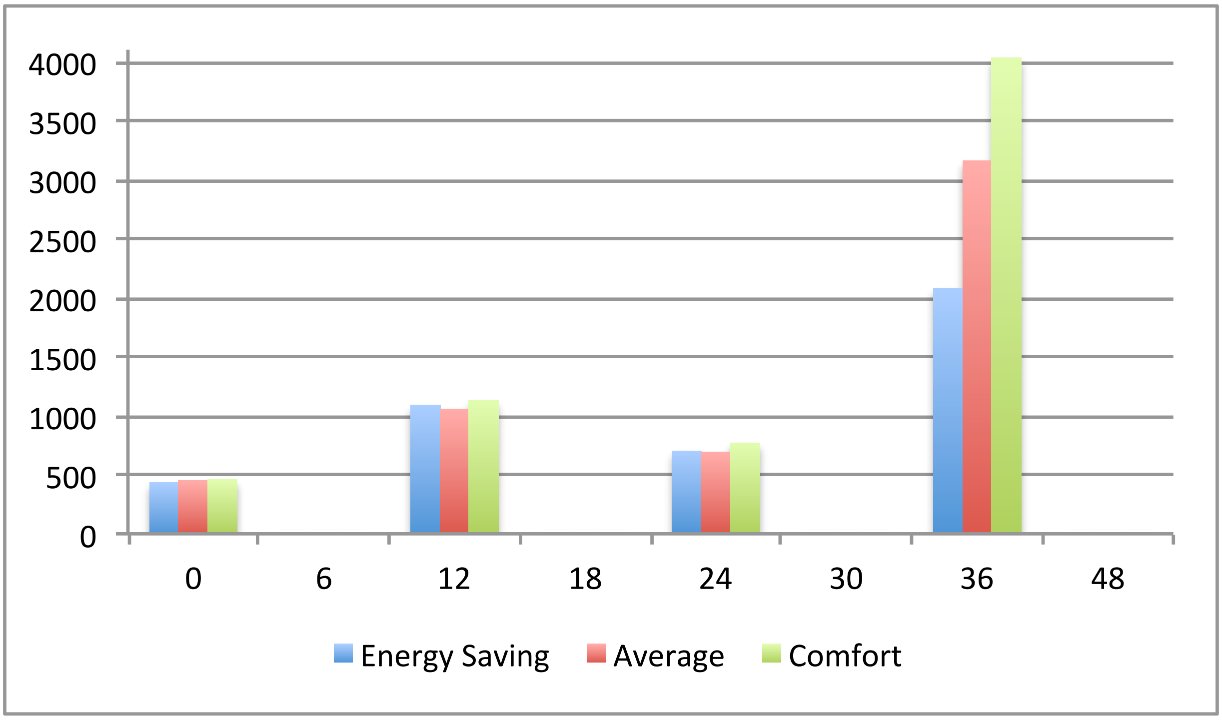

Figure 6.3 – The results of cycles of auction in each scenario

cycle of auction they return in average 254 watts; and by the end of the simulations the appliances end up with over 900 watts unused.

The reserve of power is consumed similarly in the average scenario. In the first three auction cycles the appliances usually consume all power obtained during the auctions. The fourth daily shift shown in Figure 6.4 illustrates an interesting point: during the auctions the appliances obtain all necessary power to operate, however they end the simulation with over 400 watts unused power in their reserve of power. Even the appliances have reserve of power, the smart meter does not release all the power demanded because the appliances demand more power than the cycle limit allows.

Figure 6.4 shows that in the comfort scenario the appliances finish the 3 firsts daily shift with almost none unused reserve of power; however in the last daily shift the appliances end the simulation with over 200 watts unused power.

Contrasting with Figure 6.1 there is no peak of demand in the first cycle. Figure 6.5 shows a chart of the power demanded in each of three scenarios. Even though the refrigerator needs to operate in all cycles, but it is not allowed to demand more power than the power necessary to operate in one daily shift. In the previous simulations the refrigerator had a virtual reserve of power, now this appliance depends on its bids strategy. That the aggressive strategy grants the refrigerator has better chance of getting power.

The appliances with higher priority to reserve power are following the aggressive strategy and the appliances with lower priority to reserve power are following the prudent strategy. According Table 6.2 there are 5 appliances following the aggressive strategy: refrigerator, microwave, television system,celling fan and the living room LED bulbs. Usually these appliances get power during the

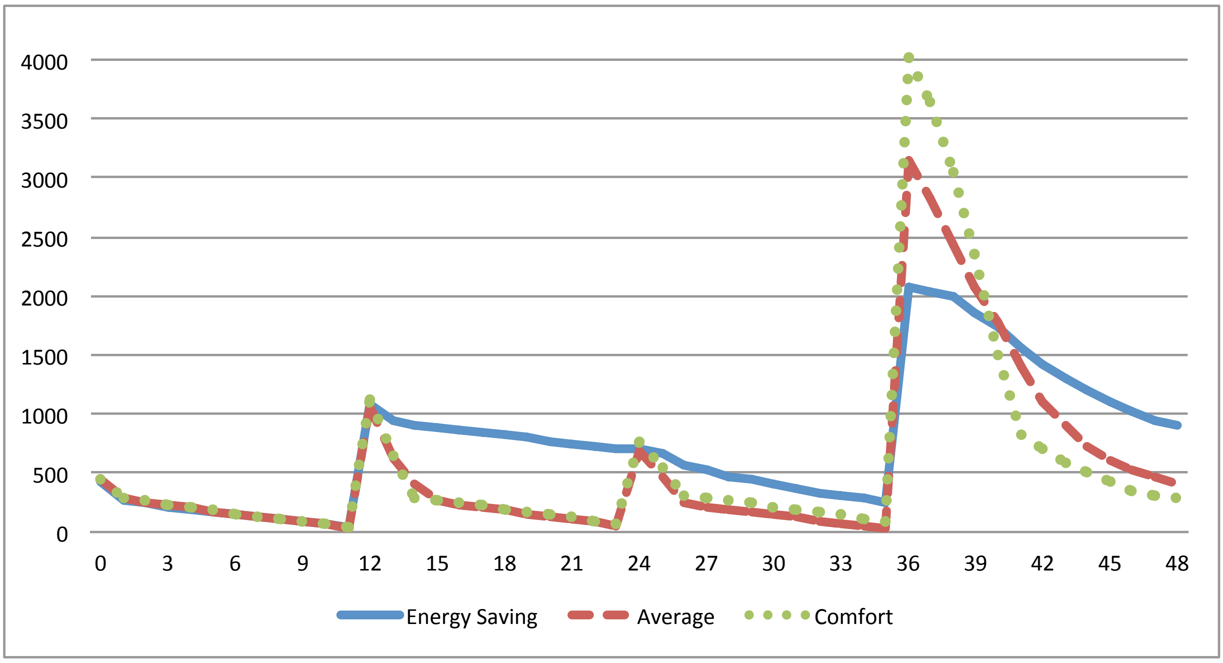

Figure 6.4 – Power reserve in each scenario

firsts auctions. The fridge and the living room LED bulbs usually get enough power in almost 99% of the cases in all the three scenarios. The celling fan and the microwave are able to get the necessary reserve of power in 100% of the cases in all the three scenarios. The television system is the most affected of these five appliances; it gets enough power in more than 98% of the cases in the comfort scenario; 95% of the cases in the average scenario; and just 63% of the cases in the energy saving scenario. This appliances fails to win auctions in the energy saving scenario not due its strategy, but because of the amount of power available to be auctioned. The aggressive strategy allowed these 5 appliances to get power before the appliances following the other strategies, consequently the smart meter gives them authorization to operate.

In the 2nd daily shift there are 4 appliances disputing power: the living room air conditioner is following the prudent strategy, the coffee maker is following the moderate strategy, the toaster bidding dynamically, and the refrigerator follows the aggressive strategy. Even though the refrigerator, coffee maker and the toaster are following different strategies they get necessary power to operate in 100% of the cases during the 2nd cycles of auctions in all three scenarios. Although the living room air conditioner is not able to get enough power in the average and energy saving scenarios; this appliance gets over to 96% of the necessary power because its strategy is less aggressive than the other three appliances. As a result the living room air conditioner fail to operate some cycles.

During the 3rd cycles of auction before the begin of the 24th cycle the vacuum and the clothes iron disputes power reserve. Both appliances are following the dynamic strategy. The vacuum and the clothes iron get the necessary energy to operate in all the three scenarios. However they fail to operate in the energy saving scenario because they demand more power than the cycle limit.

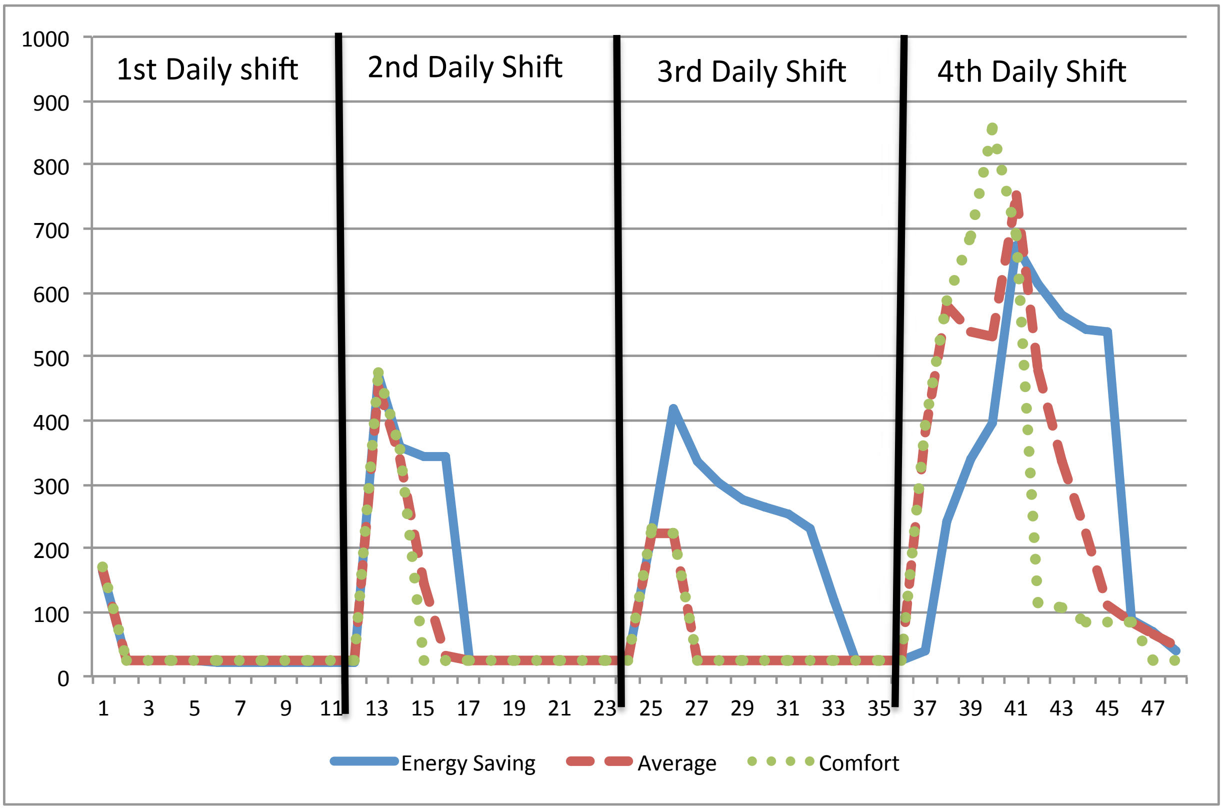

Figure 6.5 – Power demanded in each scenario

The 4th daily shift shows the most competitive cycles of auction because the power demanded in this daily shift is higher than the other 3 daily shifts. Figure 6.5 illustrates that the peak of demand in this daily shift reaches almost 900 watts.

The bedroom air conditioner has the higher demand of power, it demands 330 watts per cycle and has intention to operate in 5 cycles of its operating window. Due its strategy, this appliance fail to reserve the necessary power to operate in the 5 cycles this appliance intends to operate, because this air conditioner disputes power with 5 aggressive bidders. As a result, the air conditioner cannot operate in any cycle of the energy saving scenario; it gets enough power to operate in 50% of the cycles in the average scenario; and it gets power to operate in 4 of 5 cycles of the comfort scenario. The bedroom air conditioner strategy allows this appliance to get advantage against prudent bidders, but it is in a big disadvantage when disputes power with many aggressive bidders.

The computer and the notebook computer charger follow the fixed price strategy. The computer gets the necessary reserve of power in 100% of the cases. On the other hand, the notebook computer charger fail to win auctions; in the energy saving and in the average scenarios this appliance never gets power during the auctions; and in the comfort scenario the notebook charger gets less than 20% of the power necessary to operate in one cycle; that means this appliances end the daily shift without operating and they are obligated to return the unused power in the end of the daily shift.

The price that the computer intends to offer is quite high compared to the maximum price that most appliances intend to offer, it allows this appliance to be consider a aggressive bidder even when it is following the fixed price strategy. The notebook computer charger intends to offer a small price in very disputed auctions; so as a result they fail every time.

The last example of how the appliances strategy impacts their reserve of power involves the lightning appliances. In the living room there are three lightning appliances disputing power: 2 Living room Fluorescent light bulbs, 2 Living room LED bulbs and 1 Living room LED bulb. The 2 Living room LED bulbs follow the aggressive strategy, and get reserve of power without problems. However the other this lighting appliances from this example cannot get power in all cases; they fail to reserve power in the energy saving in 50% of the cases; and fail to reserve power in the average consumption scenario in 30% of the cases. The living room is never in the dark but in most cases it is not fully illuminated.

Appliances with priority to operate should follow the aggressive strategy, because the simulations demonstrated that appliances follow the aggressive strategy can reserve power easily than moderate or prudent appliances. We concluded that the fixed price strategy is not effective in our model since we equalized the amount of virtual credits available to the appliances. The simulations results did not show any conclusive results in relation to the dynamic strategy, if toaster and vacuum follow the moderate strategy it is possible to achieve the same results. We realized that it is possible switch the dynamic strategy with another without significantly changing the results.

6.3 Evaluation: Stochastic Simulator Versus Agent Simulator

In this section we evaluate our model comparing the results of the simulator based in a multi agent system (MAS simulator) against the results of a stochastic simulator. The stochastic simulator was developed by a research assistant and it has the objective of validating the smart home model developed in our research. This simulator is a household power consumption java simulator that inputs the appliances profile and the probability of users to use the appliances; and generates the profile of user intentions.

During the development of the simulator we met regularly to align the development of the simulator with objectives of the master research.

This section describes how we prepare the stochastic simulator to use the same appliances information used in our model; how we prepared the MAS simulator to use the user intentions and we present the integration between the two simulators. At the end of this section we present the results.

6.3.1 Experiment Setup

To configure the stochastic simulator we need to input two Json [1] files. One file describes the household appliances profile according the table 6.1

An example of Json file describing the appliances inputed in the simulator can be found in the Listing 10. It informs the existing appliances and the amount of power each one needs to operate.

```
[

        { "name": "air_conditioner"                , "power": 1000},
        { "name": "coffee_maker"                   , "power": 500},
        { "name": "coffee_maker"                   , "power": 500},
        { "name": "cellphone_charger"              , "power":1000},
        { "name": "fluorescent_light_bulb"         , "power": 40},
        { "name": "LED_light_bulb"                 , "power": 12},
        { "name": "microwave"                      , "power": 6  },
        { "name": "refrigerator"                   , "power": 50 },
        { "name": "toaster"                        , "power": 700},
        { "name": "washing_machine"                , "power": 600},

        .....

]
```

Listing 10: Example of Json file that describes the appliances used in the simulaton

The other file provides the names of the appliances, the type and the probability for each cycle of the user turns them on. The attribute *type* connect this file with the file described in Listing 10. The coffee maker, for instance, has 10% of probability to be turned on by an user at 6:00 AM and 50% at 6:30 AM. Listing 11 illustrates an example of Json file.

After loading the files and running the simulation the stochastic simulator generates the profile of user intentions that describes when the user intends to turn on or off the appliances. Listing 12 introduces an example of Json file describing when status of each appliance to each cycle. This example shows that the appliances *My toaster* is off in the first and second cycles; but it is on in the 15th cycle.

The profile of user intentions must be loaded by the MAS simulator before running the simulation. To each simulation run using the multi agent system model there is a simulation in the stochastic simulator. We modified the MAS simulator to load the user intentions; however this modification did not affect the model presented in the previous chapters.

The restrictions to demand authorization to operate were kept; the appliance can only demand authorization to the smart meter after to check if it is inside of its operating window and must have reserve of power that was gained in the cycles of auctions. To take into account the

[1] Json is not the same as Jason. It is a JavaScript Object Notation, an open standard format that uses human-readable text to transmit data objects consisting of attribute–value pairs. http://www.json.org

```
[
  { "name": "My coffee_maker"   ,"type": "coffee_maker",
    "probs": {
        "06:00": 10,
        "06:30": 50
    }
  },
  { "name": "My cellphone_charger"      ,"type": "cellphone_charger",
    "probs": {
        "00:30": 60,
        "01:00": 60,
        "01:30": 60,
        "02:00": 60,
        "02:30": 60,
        "03:00": 60,
        "03:30": 60
        }
  },
  { "name": "My refrigerator"   ,"type": "refrigerator",
    "probs": {
        ....
        "02:00": 100,
        "02:30": 100,
        "03:00": 100,
        "03:30": 100,
        ....
]
```

Listing 11: Example of Json file that describes the probability of appliances be used

user intentions we added a new restriction. The appliance can only demand authorization if the user has intention to turn the appliance on in the current cycle. Otherwise, if the user tries to turn an appliance on outside of the appliances operating window the appliance does not gain authorization to operate.

```
[
  {"appliances": {
        [
        .....

        { "name": "The toaster",
        "power": 700,
        "type": "toaster"
        "listStatus":[
                { "cycle": 1 , "status": "off"},
                { "cycle": 2 , "status": "off"},
                ....
                { "cycle": 15, "status": "on"},
        ....
```

Listing 12: Example of Json file that describes the profile of user intentions

6.3.2 Results

In this section we compare the results between the two simulators. We extracted the results and compared the power consumption between the two simulator to the three scenarios: comfort, average and energy saving.

In the comfort scenario our model introduces similar results to the stochastic simulator, but still saving power. Between the 13^{th} and 17^{th} cycles the appliances consumed in average 1040 watts in the stochastic simulator; and in the MAS simulator the appliances consumed less than 600 watts. It means a saving of 42%. Figure 6.6 shows a chart of the power consumption in the comfort scenario.

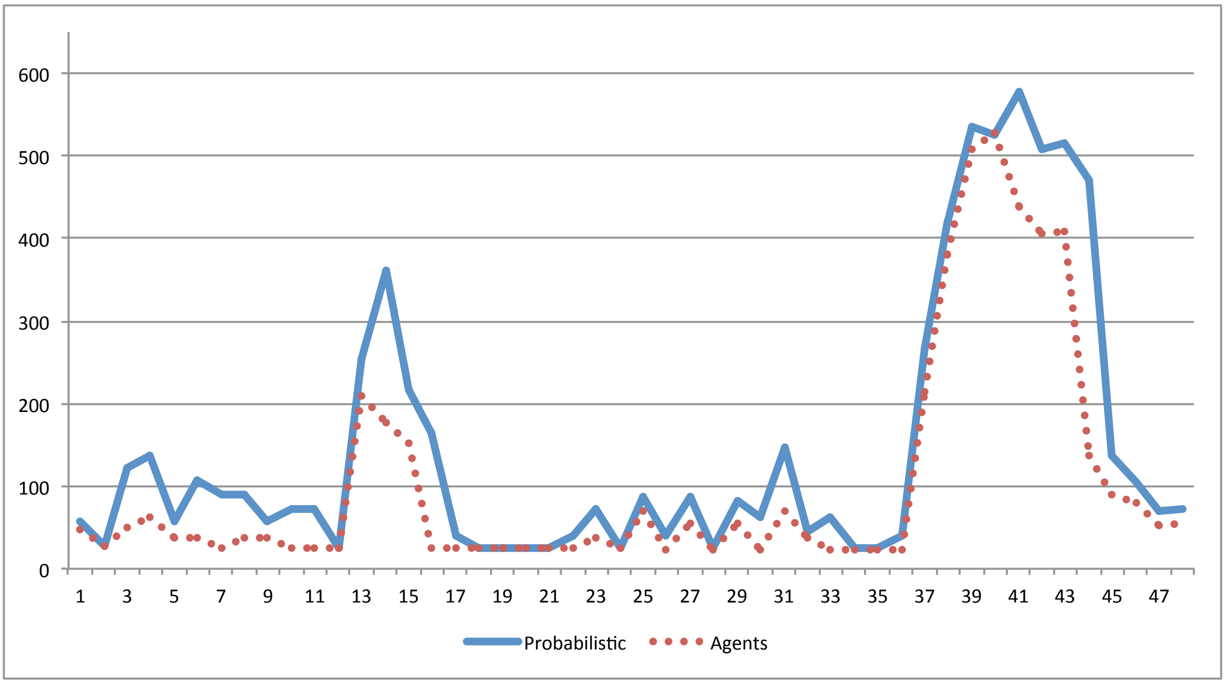

Figure 6.6 – Power consumption in the comfort scenario

Table 6.3 shows the appliances that the user turned on in the stochastic simulator. The living room air conditioner, the toaster and the washing machine are on during all their operating window; and the washing machine is on during 2 of the 5 cycles. The washing machine has the most flexible operating window because this appliances can operate in any cycle; and it is used in average twice a week [24]. During the stochastic simulation the user turn the washing machine on several times in the same day, resulting in an excessive waste of power.

The living room air conditioner, for instance, although it has an operating window of 4 cycles, it only has the intention to operate in 3 cycles. In the stochastic simulator there is no restriction permitting that the user turn the air conditioner on in the 4 cycles without problems. On the other hand the MAS simulator prohibits the air conditioner to be turned on more times than scheduled.

Table 6.3 – Appliances status between 13th and 17th cycles

Appliance	13th cycle	14th cycle	15th cycle	16th cycle	17th cycle
Living room air conditioner	on	on	on	on	off
Coffee maker	on	on	off	off	off
Toaster	on	on	off	off	off
Washing machine	on	off	off	off	on
Refrigerator	on	on	on	on	on

In the comfort scenario our model saves energy comparing with the stochastic model. Our model saves 30% comparing with the stochastic model. It is expected that the MAS model shows a better performance in the other two scenarios; and the following charts confirm that.

In the average scenario the MAS model could spend 45% less energy than the stochastic model. As can be seen from the chart there is energy saving between the 13th and 17th cycles as well. Between the 37th and 45th cycles we have a peak of demand. The appliances status in the stochastic simulations is detailed in Table 6.4. Figure 6.7 shows a chart of the power consumption in the average scenario.

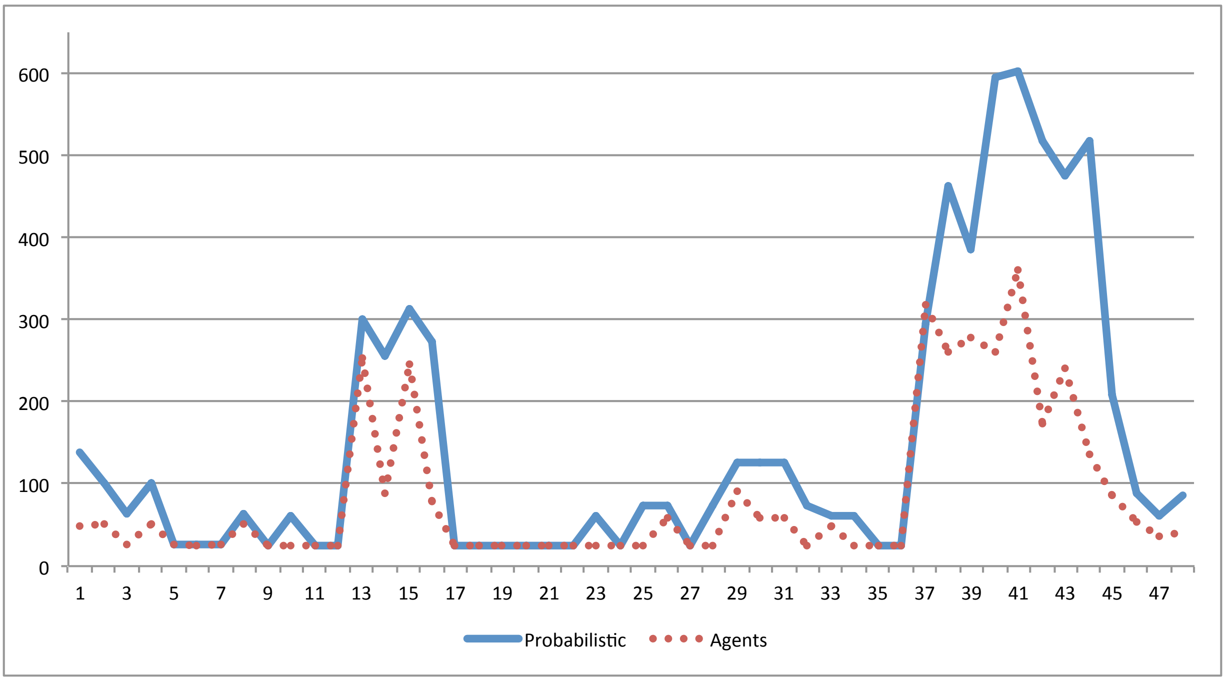

Figure 6.7 – Power consumption in the average scenario

The bedroom air conditioner and the television system has a operating window of 8 cycles and can operate in 5 of them. In the stochastic simulation the user keep these appliances on during 7 cycles. The microwave has authorization to operate between the 41st and 45th cycles and the user used this appliance in two cycles that are not in sequence. The celling fan presented a interesting behavior. It has the operating window beginning in cycle 41 and finishing in cycle 48. The user could use this appliance in all the 8 cycles during the stochastic simulations but in average the ceiling fan was kept on in only 5 of the 8 cycles.

Table 6.4 – Appliances status between 37th and 45th cycles

Appliance	37th	38th	39th	40th	41th	42th	43th	44th	45th
Bedroom air conditioner	on	on	on	on	on	on	on	off	off
Television System	off	on	on	off	on	on	on	on	on
Computer	off	off	off	on	on	on	on	on	off
Hair dryer	off	off	off	on	off	on	on	off	on
Celling_fan	off	off	off	off	on	on	on	on	on
Microwave	off	off	off	off	on	off	off	on	off
Refrigerator	on	on	on	on	on	on	on	on	on

Contrasting with the results from the stochastic simulator the MAS simulator could handle more efficiently the power consumption between the cycles 37 and 45. For example: the bedroom air conditioner, the computer and the television system were used in a maximum of three cycles; and due to the limit of power supply per cycle the user ceiling fan is mostly used by the user in the 40th and 41st cycles.

In the energy saving scenario emphasizes the control provide by the multi agent system proposed in this dissertation. The smart meter's power supply is very limited preventing that many of the user intentions are satisfied. In a household without any control the user could spend more than 7000 watts in son day, however in a household using our control system the daily power consumption is over 2000 watts, almost 70% of energy saving. Figure 6.8 shows a chart of the power consumption in the energy saving scenario.

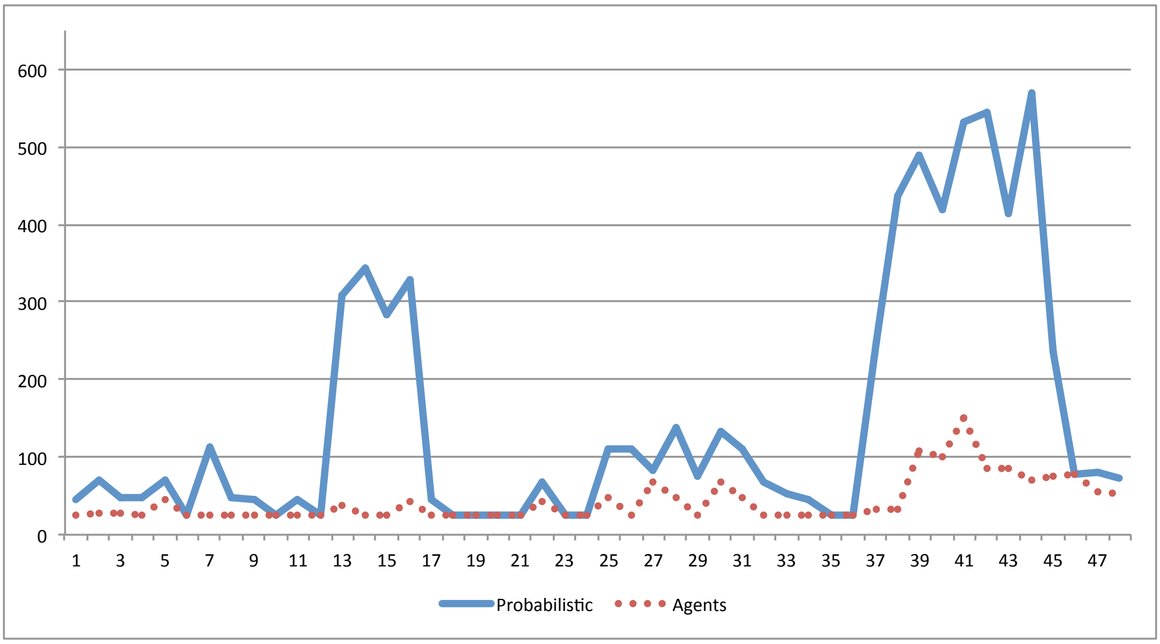

Figure 6.8 – Power consumption in the energy saving scenario

The results collected confirmed that comparing with the stochastic simulator our smart home model can avoid peaks of consumptions and provides a progressive energy saving in all three scenarios: 30% of energy saving in the comfort scenario; 45% in the average scenario and almost 70% in the most restrictive scenario.

7. CONCLUSIONS

In this dissertation we developed a smart home model designing a multi agent system to strike a balance in optimizing comfort, electrical efficiency and increasing the resilience of a household. We initially developed a theoretical study on Smart Grid and the concepts involving and on users profiles in Brazil. Afterwards we conducted a study to define protocols to set the interaction between heterogeneous electrical appliances and the smart meter; developing the household model, entities characteristics, users profiles and household configuration profile. Thereafter we develop the household model and develop a multi agent system to validate the household model.

Studying the users profiles in Brazil we identified that the user profile is changing over the years, the power demand increased significantly in the past decade and the projections indicate that the demand will keep increasing substantially. The increasing of power demand encouraged the development of an efficient control system that could help the electricity usage with parsimony.

The smart home model developed in this work is composed by two complementary control systems. The first one defines the demand2consume protocol that is responsible for avoiding peak of demand by controlling the appliances power consuming. This protocol forbids the household to consume more than the limit of power available, as a result the household became more collaborative with the power grid. However the demand2consume protocol does not take into consideration the preferences of the user, and does not provide the prioritization of power usage by appliances with more priority to the user. So, the power reserve auction-based plays this role. The power reserve auction-based allows the user to influence in the distribution of power inside of the household, by choosing more aggressive auction strategy to priority appliances and less aggressive auction strategy to appliances with less priority.

A paper with preliminary results was accepted in Workshop on Collaborative Online Organizations (COOS 2013) @AAMAS 2013 shown that it is possible to implement a demand side management in a single household. However after refining the model to include an approach to control the distribution and the power reserve we conclude that there are many possibilities and opportunities to customize a demand side management control system. Finally, the comparative tests with the probabilistic simulator proved that it is possible and worth to deploy a control system that helps the users better manage the power consumption.

As future work we will further develop the model presented in this dissertation by aggregating to the smart home model the micro generation system and to refine the control system and the communication protocol between smart entities. We want to extend the smart home model to the level of an entire neighborhood, and begin the development of an agent-controlled Microgrid. The daily execution shift will be explored in future work, in a reward and penalty approach the appliance can be encouraged to operate in the daily execution shift in exchange of some kind of reward, otherwise, the appliance can be free to operate in another daily shift while accepting some kind of penalty. We intend to study the different users profiles to understand the kind of customization that the smart system should perform to balance the demand considering the energy variation in the grid, also study the household configuration profiles (cost versus comfort) to enable the users to configure their houses balancing cost and comfort in different levels.

As future challenges it is necessary to evolve the use of the virtual credits and to explore the notation 6.1 by varying the amount of power offered and the initial value to each auction. To study different approaches to distribute the virtual credits to the appliances, the simulations shown that there are daily shifts that are more competitive than others, thus more competitive daily shifts may offer power in a higher price and in less competitive daily shifts the power may be offered cheaper. Auctions with different sizes can estimate different interests; we think in the explore this by creating a mechanism of control for the appliances decide if they prefer to bid larger or smaller lots.

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APPENDIX A – PAPER ACCEPTED IN WORKSHOP ON COLLABORATIVE ONLINE ORGANIZATIONS (COOS‘13) @AAMAS 2013

A Smart Home model to Demand Side Management

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ABSTRACT

In order to address the challenges of greener energy generation, new techniques need to be developed both to generate electricity with lower emissions and to optimize energy distribution and consumption. Smart grid techniques have been developed specifically to tackle this latter challenge. This paper aims to contribute in improving the efficiency of energy use within a single household by modeling appliances within it as a multiagent system (MAS). We model this system as a virtual organization that seeks to minimize energy consumption while reaching a tradeoff between user comfort, energy cost and limiting peak energy usage.

General Terms

Algorithms, Management, Reliability

Keywords

Demand Side-Management, Smart grid, Smart Home

1. INTRODUCTION

Electricity is the most versatile and widely used form of energy, as such, global demand is growing continuously. However, electricity generation is currently the largest single source of greenhouse gas emissions, making a significant contribution to climate change.

There are approaches within the developed world to reduce reliance on fossil fuels and move to a low-carbon economy to guarantee energy security and mitigate the impact of energy use on the environment. To mitigate the consequences of climate change, the current electrical system needs to undergo adjustments. The solution to these problems is not only in generating electricity more cleanly, but also in optimizing the use of the available generating capacity. To achieve such optimization, the *Smart Grid* comes into play. A *Smart Grid* is an electrical grid that uses information and communications technology to gather and act on information, such as information about the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity. [10]. The Smart Grid has come to describe a next-generation electrical power system that is typified by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy. Smart Grid initiatives can provide more electricity to meet rising demand and quality of power supplies, integrating low carbon energy sources into power networks. It possesses demand response capacity to help balance electrical consumption with supply, as well as the potential to integrate new technologies to enable energy storage devices and the large-scale use of electric vehicles.

Demand for electricity should be made more adaptive to supply conditions, avoiding peaks of demand, resulting in a more efficient grid with lower prices for consumers. As a result, the new electrical grid intends to get an economic balance and increase the efficiency of the current the electrical supply. Energy efficient technologies such as intelligent controls systems that adjust the heating temperature, lighting can help with the management of consumption in buildings and houses. This intelligent control system can give consumers control over the amount of electricity they use. Furthermore, the intelligent control system can integrated into the power grid through equipment capable of collecting data about electricity consumption and of communicating with others entities in the power grid. A key element that allows all of the emerging smart grid technologies to function together is the interactive relationship between the grid operators, utilities, and the user. Controls in the household and appliances can be set up to respond to signals from the energy grid to minimize the energy use at times when the power grid is under stress from high demand, or even to shift some of their power use to times when power is available at a lower cost. This intelligent control system inside a household introduce the concept of *Smart Home*.

Within the smart grid, a smart home is a household that has highly advanced automatic systems responsible for manager and control the smart appliances. Our main contribution is an agent-based smart home model whereby individual autonomous agents are deployed to control each household energy consuming device, as well as an agent coordinating them all through the energy meter. This model should allow a smart home to become more collaborative with the electric grid by balancing energy demand, increasing the resilience of the household as well as optimizing user comfort. The rest of this paper is structured as follows: Section 2 reviews the background required for our definition of a smart home model; Section 3 presents the Smart Home model itself; Section 4 evaluate how the appliances are managed using the

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model proposed; and finally, Section 5 concludes this paper and presents future work.

2. BACKGROUND

In this section, we briefly explain the organization of the electric power industry and its three major sectors. Moreover, we introduce key concepts relating to the smart grid, and some of its associated technologies.

2.1 Electric Power Industry

The power industry is divided into three major sectors: generation, transmission and distribution.

Electricity *generation* is the large-scale process of generating electric power for industrial, residential, and rural use, generally in stationary plants designed for that purpose. Steam turbine generators, gas turbine generators, diesel engine generators, alternate energy systems (with exception of photovoltaic power cells), even nuclear power plants all operate on the same principle - magnets plus copper wire plus motion equals electric current. The electricity produced is the same, regardless of source. A power station (also referred as power plant) is an industrial facility for the generation of electric power. At the center of nearly all power stations is a generator, a rotating machine that converts mechanical power into electrical power by creating relative motion between a magnetic field and a conductor [6].

Electric power *transmission* is the bulk transfer of electrical energy, from generating power plants to electrical substations located near demand centers. Substations transform voltage from high to low, or the reverse, between the generating station and consumer, electric power may flow through several substations at different voltage levels. Transmission lines, when interconnected with each other, become transmission networks [4].

Electricity *distribution* is the final stage in the delivery of electricity to end users. A distribution system's network carries electricity from the high-voltage transmission system and delivers it to consumers. Substations are needed to step up and down the voltage, since long range transmission is more efficient at very high voltages. Typically, the network would include medium-voltage (less than 50 kV) power lines, substations and pole-mounted transformers, low-voltage (less than 1 kV) distribution wiring and sometimes meters. At a distribution substation, a substation transformer takers the incoming transmission-level voltage (35 to 230 kV) and steps it down to several distribution primary circuits. The distribution infrastructure is extensive, after all, electricity has to be delivered to customers concentrated in cities, suburbs and very remote regions [17].

2.2 Smart Grid

Smart Grid generally refers to a class of technologies using computer-based remote control and automation. These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries [10]. Murphy et al. [11] define the term Smart Grid as a modern electricity system that uses uses sensors, monitors, communication, automation and computers to improve the flexibility, security, reliability, efficiency and safety of the electricity system.

The benefits of the smart grid are substantial. These benefits will result from improvements in the following six key value areas [8]:

- **Reliability**: by reducing the cost of interruptions and power quality disturbances and reducing the probability and consequences of widespread blackouts;
- **Economics**: by keeping downward prices on electricity prices, reducing the amount paid by consumers;
- **Efficiency**: by reducing the cost to produce, deliver, and consume electricity, however providing the same or better level of quality service;
- **Environmental**: by reducing emissions by enabling a larger penetration of renewables and improving efficiency of generation, delivery, and consumption;
- **Security**: by reducing the probability and consequences of manmade attacks and natural disasters; and
- **Safety**: by reducing injuries and loss of life from grid-related events.

Ramchurn et al. [13] argue that the Smart Grid provides significant new challenges for research in AI since Smart Grid technologies will require algorithms and mechanisms that can solve problems involving a large number of highly heterogeneous actors. Demand-Side Management, electric vehicles, virtual power plants, energy prosumers and self-healing networks are some of the key components that deserve attention in smart grid research.

A safe and efficient electricity grid should be in perfect balance. Schweppe et al. highlight reasons why demand for electricity should be made more adaptive to supply conditions [16]. They note that if peaks of demand were flattened, it would result in longer term and cheaper production contracts, resulting in a more efficient grid with lower prices for consumers.

Demand-side management (DSM) is used to describe the actions of a utility, with the objective of altering the end-use of electricity, whether it be to increase demand, decrease it, shift it between high and low peak periods, or manage it when there are intermittent load demands. In other words DSM is the implementation of measures that can help the customers to use electricity more efficiency. Existing approaches to reduce demand have been limited to either directly controlling the devices used by the consumers (e.g., automatically switching off high load devices such as air conditioners at peak times), or to providing customers with tariffs that deter peak time use of electricity. With the deployment of smart meters, it is possible to make real-time measurements of consumption, providing every home and every commercial and industrial consumer with the ability to automatically reduce load in response to signals from the grid. An important AI challenge in demand-side management is designing automation technologies for heterogeneous devices that learn to adapt their energy consumption against real-time price signals when faced with uncertainty in predictions of future demand and supply.

The "Model City Mannheim" (moma) project is an example of smart grid initiative; the project focuses on researching the implications of innovative IT for the energy grid. The project is part of the E-Energy project framework initiated and partly funded by the German federal ministries for economics and environment [15].

2.3 Smart Home

Smart Home is the term commonly used to define a residence that has appliances, lighting, heating, air conditioning, TVs, computers, entertainment audio and video systems, security, and camera systems, etc, that are capable of communicating with one another and can be operated remotely by a control system. This control system allows the definition schedules for operation or remote operation by phone or over the internet.

Within a smart home, a smart meter is responsible to provide the interface between household and the energy provider. Replacing the old electromechanical meter, these meters operate digitally, and allow for automated and complex transfers of information between the household and the energy provider. For instance, smart meters can receive signals from the energy provider to help the household balance demand and reduce energy costs. Smart meters also provide utilities with more information about how much electricity is being used.

Smart appliance is a device that allows access and operation through an automated management system. Smart appliances can also be able to respond to signals from the smart meter to avoid using energy during times of peak demand.

This new generation of household devices can be distinguished by three characteristics [1]:

- Instrumented: devices provide increasingly detailed information about and control over their own operation and also provide information about the environment in which they operate.
- Interconnected: devices can communicate and interact, with people, systems and other devices. It supports the aggregation of information and control of devices throughout the network.
- Intelligent: devices can make decisions based on data, leading to better outcomes, supporting the optimization of their use, both for the individual consumer and for the service provider.

Current smart appliances and their communications technology are very heterogenous among different vendors, with standardization in its early phases. In this scenario of heterogeneous devices and protocols, it is necessary to adopt an abstract, standards-based view of the new smart grid system as early as possible. In an ideal smart grid environment, all smart grid appliance functions, device connectivity, and device protocols are be standardized in order to avoid multiplied maintenance effort and vendor lock-in for proprietary components [15].

One challenge to the realization of the smart home vision is the need to integrate a large number of entity interfaces, networking protocols and technologies and a variety of applications and services already deployed in the home today. Two types of communication protocols may be considered. The first one is LAN-like protocols to enable appliances to communicate with each other inside of the household. The second type of communication protocol is a WAN-like, this protocol allow a wider communication with other elements of the power grid. For example, each household appliance can take advantage of the household router to connect directly to service in the network [1].

The deployment of a smart home goes beyond the improvement of a household, for example, if a set of smart homes work together it is possible avoid peak of demand in the whole power grid. For instance, a smart air conditioner might extend its work time slightly to reduce its load on the grid; while not noticeable to the user, millions of air conditioners acting the same way could significantly reduce the load on the power grid. Likewise, a smart refrigerator could defer its defrost cycle until off-peak hours, or a smart dishwasher might defer running until off-peak hours.

A smart home can use micro generation system to supply the household demand. Rooftop solar electric systems, small wind turbines and small hydropower are examples of micro generation system. Moreover, smart homes with their controls system can help to effectively connect all micro generating systems to the grid. For instance, a community of smart homes with photovoltaic panels can use their solar array to keep the lights on even when there is no power coming from the grid.

3. SMART HOME MODEL

The estimated average monthly consumption of appliances presented in this work comes from a company which operates in the areas of generation, transmission and distribution of electricity. Table 1 shows a group of appliances for a household used by a family of three. In this table we have the list of appliances, the power each one consume per hour, the amount of each type of appliance that exists in the household, the time that each appliance is switched on daily and the daily consumption of each appliance.

Table 1: Consumption of a household

Appliance	Power (W)	Quantity	Hours per day	kwh
Air condicioner	950	1	2	57
Vacuum	1000	1	0,10	3
Laptop	200	2	0,25	3
Clothes Iron	1000	1	0,10	3
Fluorescent bulb	32	6	3	17,28
LED bulb	13	5	3	5,85
Washing machine	600	1	0,25	4,50
Microwave	1400	1	0,05	2,10
Refrigerator	50	1	24	36
Television	150	1	2	9
Roof fan	200	1	3	18

3.1 Domestic Appliances

Within the domestic energy domain, it is common to characterize domestic appliances under specific categories: wet and cold appliances, water heating, space heating, cooking and lighting appliances, periodic load and miscellaneous appliances [7] [12]. Table 2 illustrates the types of domestic electrical appliances.

The different categories imply different behaviors. Wet appliances typically involve set periods of time, programmed by the user or a device controller. Cold appliances have continuous demand, however, this demand is associated to weather variation, e.g. in the summer cold appliances such as a refrigerator need more energy to keep the temperature

Table 2: Domestic device groups

Type	Examples
Wet	Washing machine, tumble dryers, dishwashers
Cold	Refrigerators, fridge-freezers
Lighting	Incandescent light bulbs, led lamps, fluorescent light bulbs.
Cooking	Electric ovens, microwaves, grill, coffee and tea makers, etc.
Temperature Controller	heat pumps, radiators, air conditioners
Periodic Load	laptop computers, cell phones, tablet computers, electric bicycles, battery chargers
Entertainment	television, home theater, radio, etc
Personal Care	hair dryers, electric toothbrushes, electric razors
Miscellaneous	sewing machines, clothes irons, vacuum cleaners, garden equipment, electric blankets, computer printers, slide projectors, etc.

compared to the energy needed in winter. Temperature controllers have power consumption related to their usage and user routine, when there are users at home, temperature controllers and water heating have power consumption, otherwise when there is nobody at home they should be off or in a standby state. Lighting, cooking appliances, entertainment, periodic load and miscellaneous are much more dependent on the user lifestyle and preferences.

3.2 Appliances Description

All devices considered in this model have only two possible states, ON and OFF, and change between these states via their internal schedule or an external command. Moreover, we assume that all appliances have similar energy consumption distribution during all the days of the year. Future studies can consider additional states, such as a standby state. Another future study can expand energy consumption profiles within the year e.g. different consumption for workdays and weekends as well as different consumption during summer and winter. For this model we consider a typical domestic profile with fixed time intervals consisting of single days, divided in periods of half-hour. Each time slot $t \epsilon$ T where T = 1,...,48 [18] [12].

Each appliance is responsible to request the power required for each cycle, and cannot demand more power than needed to operate in one cycle, even if there is energy left. An exception to this rule is related to the appliances that must operate continuously, such as a refrigerator, in this case the appliance must request all necessary power to operate in the operation window. Each appliance must execute within its predefined operation window.

The attributes defined for each appliance are: power, the number of cycles that the appliance needs to operate per day, category and operation window. Each appliance is described using the following notation:

$$appliance(Pow, Cycles_number, Categ, Window[Start, End])$$

3.2.1 *Wet appliances*

Devices in this category usually work in well-defined periods of time, e.g. washing machines work one to two hours per use. The user has three different periods of time to schedule wet appliances, e.g. 8:01 AM to 4:00 PM, 4:01 PM to 00:00 AM and 00:01 AM to 8:00 AM. Once the appliance starts working, the state switches from OFF to ON and during the defined period of time, the device must remain in the ON state, switching to OFF after finishing its work.

3.2.2 *Cold appliances*

Cold appliances work to satisfy certain configuration constraints, e.g. if a refrigerator is programmed to keep its temperature at 5 degrees celsius, it should request power in order to maintain this temperature. For this type of device, power demand variation is associated to weather changes instead of user lifestyle, routine and preferences. So, for example, in summer the device might require a little less power, otherwise, in winter the device requires more power to keep the programmed temperature.

3.2.3 *Temperature Controllers*

Temperature controllers typically demand power according users needs, e.g. the air conditioner should work to make the user comfortable. For example, summer temperatures in certain countries can easily reach 35 celsius degrees and the user wants to get home and get cooler temperature, so the air conditioner should start working some time before the user arrives home.

3.2.4 *Lifestyle appliances*

This last category includes lighting, cooking appliances, entertainment, periodic load and miscellaneous appliances. All household appliances from these categories are strongly related to user routines, preferences and lifestyle, e.g. users who likes cooking, users who have the lifestyle focused on mobile technologies probably charge their mobile devices periodically. Assuming that this kind of users does not yield in their preferences, they will use the appliances from this category, without taking into consideration the cost involved.

4. EXPERIMENTS AND EVALUATION

In this section we describe the setup used in our experiments. This set up includes the environment used in the simulations that contains the daily shift configuration, the appliances profile and the group of appliances used in the simulation. We follow with a description of the implementation of our simulation, including the appliances setup, the local allocation protocol used to coordinate the simulation and three different scenarios used during the simulations.

4.1 Experiment Setup

Based on average household consumption within a developing country, we assume that a household consumes during summer time 173 kWh per month or 5.77 kwh per day.

Each day is divided in 48 cycles of 30 minutes, the first cycle starts at 0:00 AM and ends at 00:29 AM. Each appliance can be classified according their daily execution shift, there are 6 different options for which each appliance can be scheduled to operate, in this simulation we define that just one option can be chosen and the appliance is now allowed to operate out of its daily execution shift. Table 3 illustrates the daily shifts.

Table 3: Day shift execution

Day Shift	Begin	End	Initial Cycle	Final Cycle
Dawn	00:00	05:59	1	12
Morning	06:00	11:59	13	24
Afternoon	12:00	17:59	25	36
Night	18:00	23:59	37	48
All	00:00	23:59	1	48
Any	–	–	–	–

If an appliance has its day shift as "Morning", it can can operate between 06:00 AM and 11:59, however if an appliance is scheduled to operate during the entire day, its day shift must be "All", meaning that this appliance wants operate in all cycles. Moreover if an appliance has the value "Any" in its day shift, it means there is no priority to this appliance, and it can operate in any cycle. Appliance are also classified in category described in Section 3.1. Finally, each appliance has an operating window, the interval on which the appliance must operate. The appliance must operate within its operating window, it is not allowed the operate outside the cycles defined in the operating window.

4.2 Implementation

Our simulation was implemented using JaCaMo[1], a framework for Multi-Agent Programming that combines three separate technologies. Each of the three independent platforms composing the JaCaMo framework has its own set of programming abstractions and its reference programming model and meta-model. JaCaMo combines the use of three technologies, Jason[2] [3] for the development of autonomous agents, Cartago[3] [14] for development of virtual environments and Moise[4] [9] for developing the organizational model for multi agents based on concepts as roles, groups, mission and schemes.

The implementation of the model was organized in order to respect the proposal of JaCaMo framework. The organization with the roles, objectives and schemes are implemented at the Moise level. The environment artifacts that define he limit of power per day and limit of power per cycle are implemented at the Cartago level. Finally the implementation of agents is done at the Jason level.

4.2.1 Moise *Level*

The roles defined at the Moise level are: the smart meter and appliances that are divided according to the categories described in Section 3.1 The groups defined in this layer represent the power consumption described in Section 3.2

We defined one scheme to coordinate the power consumption. This scheme covers four goals. The first goal is set to control peak of demands, this goal is achieved through mission control peak demand, only the *SmartMeter* can assume this mission. The three other goals are energy demanded, energy received and executed in operation window; these three goals are achieved through the missions: demand energy, receive energy and execute in operation window; all appliances must commit to these three missions.

[1]http://jacamo.sourceforge.net/
[2]http://jason.sourceforge.net/
[3]http://cartago.sourceforge.net/
[4]http://moise.sourceforge.net/

4.2.2 Cartago *Level*

Two artifacts are defined in the environment implemented at Cartago level, the first artifact control the cycles: when the cycles start, the cycle progress and a routine to stop the cycle progress. All agents in the simulation have knowledge of this artifact.

The second artifact control the power load: the limit of power to each cycle, the limit of power per day and control the appliances consumption. This artifact is known only by the controller (*SmartMeter*).

4.2.3 Jason *Level*

This level includes the agents implementation, the agents can assume the roles defined at Moise level, some roles may be assumed by more than one agent, for example, the role 'temperature controller' can be assumed by the air conditioner or the ceiling fan. Each objective defined in the functional specification at Moise level is met by plans implemented in the agents.

Each agent represents an appliance, and their individual behaviour takes into consideration the appliance types from 3.1. Consequently, we implemented a generic appliance-agent that includes initial beliefs common to all appliances, as well as a common plan library. At runtime, each appliance-agent commits to the same missions over time, depending on the appliance it controls.

4.3 Setup

As described in Section 3.2 the attributes defined for each appliance in this simulation are: power, the quantity of cycles it wants operate per day, category and operating window. The group of appliances used in the simulation is described in Table 4. This table describe the appliances used in the simulations, for each appliance we have: the power required for operation, the number of cycles they operate per day, the day shift, the category and the operating window.

4.4 Load Allocation Protocol

The Smart Meter has the responsibility of releasing load for each appliance; monitoring the set of appliances so they do not operate out of their operating window; control the peak of demand per cycle and control the limit of load per day; and prioritizing the order that the appliances demand power, for example: the appliances that need operate during all day should demand power first, after that coming the morning appliances, afternoon, appliances, night appliances, dawn appliances and just after those appliances the "Any" appliances can demand load.

The appliances have to monitor their operating window, request the necessary load from the Smart Meter at the start of an operating window and in each cycle, negotiate with the Smart Meter if can operate or should wait until next cycle.

When the device is in the first cycle of their operating window, it should negotiate with the smart meter all the power necessary to operate in the current operating window. Get the quantity of power necessary does not guarantee that the appliance will operate in all cycles that it intends, the appliance still must negotiate with the smart meter if it can or cannot operate in each cycle.

The smart meter sends power to the appliance after verifying there is capacity remaining in the current cycle. If an appliance demands 100 watts and there is 90 watts remaining, the smart meter will not release any load. In this

Table 4: Appliances used in the simulation

Appliance	Power (W)	Cycles/day	Daily Demand	Day Shift	Category	Operating Window
Air conditioner	950	4	1900	afternoon	Temperature Controller	27 to 34
Washing machines	600	0.5	150	any	Wet	1 to 48
Coffee maker	500	0.2	50	morning	Cooking	13 to 13
Fridge	50	48	1200	all	Cold	1 to 48
Television System	430	5	1075	afternoon	Entertainment	28 to 36
Cellphone charger	15	2	15	dawn	Periodic Load	1 to 12
Ceiling fan	120	6	360	night	Temperature Controller	41 to 48
2 Living room Fluorescent light bulbs	40	4	80	night	Lighting	37 to 42
Bathroon Fluorescent light bulbs	20	4	40	night	Lighting	40 to 44
Kitchen Fluorescent light bulbs	20	4	40	night	Lighting	37 to 42
Bedroom Fluorescent light bulbs	20	4	40	night	Lighting	40 to 48
2 Living roon LED bulbs	10	6	30	night	Lighting	37 to 42
2 Living roon LED bulbs	5	6	15	night	Lighting	37 to 42
3 Dining roon LED bulbs	15	2	15	night	Lighting	39 to 43

scenario the smart meter just controls if the limit of load per cycle and limit of load per day is not violated, the first appliance that demand, will be served.

4.5 Runs

Three difference scenarios were considered in order to compare the results. The first one focus in an average consumption during all day, after analyze the average of demand required for a household where 3 people live together [5], we assumed that the peak of demand allowed in each cycle should be 10% of the daily load. The second scenario focus in the user economy, the peak of demand per cycle allowed is 3.33% of the daily load (one third of the peak allowed in the first scenario), in this scenario the priority is save energy and the user comfort steps aside, the appliances may fail to operate because the competition for power is high.

In the third scenario the user comfort is top priority, this scenario allows a peak of demand per cycle of 60% of the daily load, the appliances operating window are distributed in the 48 cycles because we assume that the group of appliances defined here does not operate together, however the peak of demand defined in this scenario allows all appliances to operate at the same time.

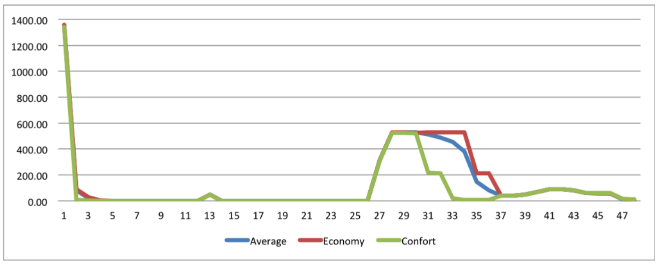

Figure 1: Load demanded in each scenario

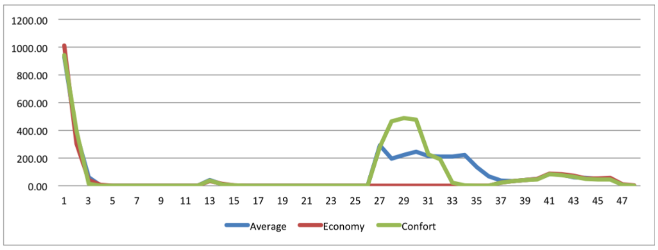

Figure 2: Load received in each scenario

4.6 Results

To empirically evaluate these scenarios, we executed each of them 100 times. We extracted and compared the total load demanded in each cycle, the total load received in each cycle and the total load consumed in each cycle.

Figure 1 shows a chart of the load demanded in each of three scenario. Figure 2 shows a chart of the load received in each of three scenario. Figure 3 shows a chart of the load consumed in each of three scenario.

As can be seen in the Figure 1, there is a peak of demand in the first cycle, this peak occurs because of the energy demanded from the fridge, as the fridge must operate in all cycles, it is allowed that the fridge demand all necessary power in the first cycle. In addition, the fridge sent a power request to the smartMeter in the cycle 1 in 100% of the cases, besides the fridge received the power demanded during the first cycle in 73% of the cases and received during the second cycle in 27% of the cases.

The air conditioner is programed to begin the operating window over the 27th cycle and the television system operating windows begins at 28th cycle, together they need more than 500 watts to operate, this causes a peak of demand be-

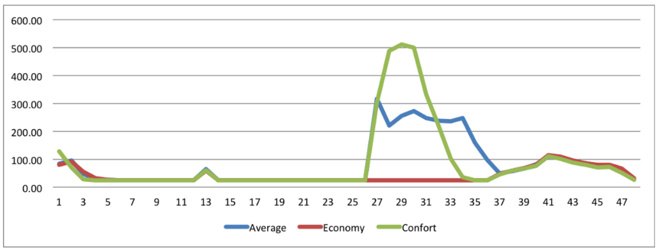

Figure 3: Load consumed in each scenario

tween cycles 26 and 36. In the economic scenario (red line), both the air conditioner and the television system demands more power than the limit allowed per cycle, the cycle limit is 200 watts that represent 3.33% from the available daily load and the air conditioner and television system demand 314 watts and 215 watts per cycle respectively. As a result, there is a peak of demand during the operating windows of these appliances (Figure 1), however the smart meter does not release any power during the cycles 26 and 32 (Figure 2).

In the average scenario (blue line) the behavior of the air conditioner and the television system are different. The cycle limit allows the just one of then receive energy per cycle resulting that the power usage is distributed along the cycles, avoiding peaks of demand, in cycles that both appliances could demand power together (cycles 28 and 33) sometimes the air conditioner receives power and the television system does not and sometimes the opposite.

In the comfort scenario we can see that the air conditioner and the television system get energy in the firsts cycles of their operating window, it is possible because the cycle limit is higher than their demand.

After cycle 37 the light system begins operates, as the sum of all lights is smaller than all cycle limits configured in all three scenarios it is not possible observe any kind of variation in the light appliances. It is necessary to modificate the light appliances profile to observe the behavior of the lights being affected in the different scenarios.

5. CONCLUSIONS AND FUTURE WORK

The electrical power system is now one of the most critical components of the infrastructure on which modern society depends. It delivers electrical energy to industrial, commercial and residential consumers, meeting an ever-growing demand. To satisfy both the increasing demand for power and the need to reduce carbon emissions, we need an electric system that can handle these challenges in a sustainable, reliable and economic way.

Development of Smart Grid technologies is accelerating, however the potential of the Smart Grid opportunity for solution providers is still unclear. Smart meters are often the first application deployed in the implementation of a Smart Grid, consequently, it is expected that in 2014 the numbers of Smart meters deployed reach 30 million. Furthermore, it is estimated that the global market potential for Smart Grid solution providers and equipment manufacturers will total somewhere between $15 billion and $3 billion annually by 2014, splitting the value along three main business segments: grid applications, advanced metering infrastructure and customers applications [2]. Based on analysis of the literature, we presented a possible application of software agents in the Smart Grid. By extending the Smart Home model to the level of an entire neighborhood, it should be possible to implement an agent-controlled Microgrid.

As future work we will further develop the model presented in this paper by aggregating to the Smart Home model the micro generation system and the evolve the control system and the communication protocol between smart entities. The daily execution shift will be explored in future work, in a reward and penalty approach the appliance can be encouraged to operate in the daily execution shift in exchange of receive a reward, otherwise, the appliance can be free to choose operate in other daily shift however a penalty will be applied. We intend to study the different users' profiles to understand the kind of customization that the smart system should perform to balance the demand considering the energy variation in the grid, also study the household configuration profiles (cost versus comfort) to enable the users to configure their houses balancing cost and comfort in different levels.

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