FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Smart Grids Community Providers and the Tariff Problem

Agent Process Models for Energy Market Simulation

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DISSERTATION

Mestrado Integrado em Engenharia Informática e Computação

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Abstract

In the past, electric grids were a one-way infrastructure where electricity flowed from producers to consumers. With the evolution of the electric devices and the technology that supports such grids, the whole business behind the smart grids evolved towards the concept of Smart Grid. A Smart Grid is smarter in the sense of automation, and optimisation is also considered: automatic negotiation, load prediction, as well as metering, demand changes and multiple other services could be now applied, creating new energy markets and services. Therefore, a two-way dialogue is available, and both electricity and information can be exchanged between the utility and its customers. Smart grid innovations are also making possible to develop more complex energy markets, where a decentralised scenario approach replaces centralisation. Instead of consuming from big producers that have a constant load at the cost of enormous carbon footprint quantities, decentralised energy from greener producers such as windmills and solar panels are becoming a reality for significant amounts of energy.

In this new model, some issues regarding availability arise, such as dynamic pricing and multiple tariffs according to the energy provenience as well as customer mobility, enabling more dynamic markets and making the environment and customers' decisions more complex. For example, consumers will have more tariffs to choose, and that might not be adequate in the long run. Today's energy tariffs are not generally liberalized. In the same way, they are too generic in the sense they try to maximise clients and are not designed for a particular group of clients.

Literature in energy markets highlights the need for study and development of new *community markets* models as an architecture in which consumers with similar profiles come together to obtain better conditions and more appropriate tariffs. A manager called *community provider* negotiates tariff conditions on behalf of the community members it represents. In a regular provider's perspective, the community provider is just another client, but from its consumers, it represents a specialised provider that knows their reality and could better express their interests in its tariffs.

The goal of this work is to study the characteristics of community energy markets and evaluate whether customised tariffs for a particular group of customers could help to keep tariff subscription stability and clients more satisfied. Thus, in this work, we developed a Multi-Agent System composed of three different types of agents: consumer, provider and a community provider. All agents are modelled using the Agent Process Modelling methodology. Agent behaviours are represented with Business Process Model Notation (BPMN), and the Multi-Agent System comes to life implemented through a distributed microservices approach. Two different simulation scenarios were designed to compare if a community provider can offer more suitable tariffs to its clients. The obtained results point that if customer group with similar profiles could find more appropriate tariffs, they should maintain the same tariff for a greater time. Further work can reveal more details about the community cohesion and community provider election mechanisms shall be studied in order to gain knowledge about community markets in general.

Resumo

No passado, as redes elétricas eram uma infraestrutura unidirecional onde a eletricidade fluía dos produtores para os consumidores. Com a evolução da tecnologia nasceu o conceito *Smart Grid*. Uma *Smart Grid* é mais rede mais inteligente, que com a evolução novas funcionalidades surgiram tais como: negociação automática, previsão e medição de carga, mudanças de demanda e vários outros serviços poderiam ser aplicados agora, criando novos mercados e serviços de energia. Portanto, um diálogo bidirecional está disponível, e eletricidade e informações podem ser trocadas entre fornecedores e os seus clientes. As inovações das *Smart Grids* também estão a possibilitar o desenvolvimento de mercados de energia mais complexos, nos quais uma abordagem de cenário descentralizada substitui a centralização.

Nesse novo modelo, surgem algumas questões relacionadas à disponibilidade, como tarifas dinâmica e tarifas múltiplas de acordo com a proveniência de energia e a mobilidade do cliente, permitindo mercados mais dinâmicos e tornando o ambiente e as decisões dos clientes mais complexos. Por exemplo, os consumidores terão mais tarifas a escolher, e isso pode não ser adequado a longo prazo. As tarifas energéticas de hoje não são geralmente liberalizadas. Da mesma forma, as tarifas são muito genéricas no sentido em que tentam maximizar os clientes e não são projetados para um grupo específico de clientes.

A literatura nos mercados de energia destaca a necessidade de estudo e desenvolvimento de novos modelos *community markets* como uma arquitetura na qual consumidores com perfis similares se reúnem para obter melhores condições e tarifas mais apropriadas. Um gerente chamado textit community provider negocia as condições tarifárias em nome dos membros da comunidade que representa. Na perspectiva de um fornecedor, o fornecedor da comunidade é apenas outro cliente, mas, de seus consumidores, representa um fornecedor especializado que conhece a sua realidade e pode expressar melhor os seus interesses nas suas tarifas.

O objetivo deste trabalho é estudar as características dos mercados de energia comunitários e avaliar se as tarifas customizadas para um determinado grupo de clientes podem ajudar a manter a estabilidade de clientes numa tarifa e se os clientes ficam mais satisfeitos. Assim, neste trabalho, desenvolvemos um Sistema Multi-Agente composto por três tipos diferentes de agentes: consumidor, fornecedor e fornecedor comunitário. Todos os agentes são modelados usando a metodologia *Agent Process Modeling*. Os comportamentos dos agentes são representados com o *Business Process Model Notation* (BPMN), e o sistema Multi-Agent é implementado através de uma abordagem de microsserviços distribuída. Dois cenários de simulação diferentes foram projetados para comparar se um provedor comunitário puder oferecer tarifas mais adequadas aos seus clientes. Os resultados obtidos destacam que, se os grupos de clientes com perfis semelhantes puderem encontrar tarifas mais adequadas, devem manter a mesma tarifa por um tempo maior, tornando o mercado mais estável. O trabalho adicional pode revelar mais detalhes sobre a coesão da comunidade e os mecanismos de eleição do fornecedor da comunidade devem ser estudados para obter um melhor conhecimento sobre os mercados de comunidade em geral.

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I begin by thanking my supervisor, Doctor Daniel Castro Silva, and to my co-supervisor, Thiago Reis Pedroso Munhoz Rúbio, for all the patience, opinions, criticisms and above all for the support and availability that they dedicated to me throughout this work.

I also want to thank my friends who shared this journey; it was an amazing journey. For last, I thank my family, in particular, my parents, brothers and grandparents for all the patience, sacrifices and unconditional support they have given me.

Nuno Ramos

"Confidence is ignorance.
If you're feeling cocky, it's because there's something you don't know."

Eoin Colfer, Artemis Fowl

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Abbreviations and Acronyms

ABM	Agent-Based-Model
API	Application Programming Interface
APM	Agent Process Modelling
BDI	Belief-Desire-Intention
BPMN	Business Process Model and Notation
CAS	Complex Adaptive Systems
CPP	Critical Peak Pricing
DER	Distributed Energy Resources
DSM	Demand Side Management
HTTP	HyperText Transfer Protocol
ICT	Information Communication Technology
ISO	International Organization for Standardization
JADE	Java Agent Development Environment
MAS	Multi-Agent System
MASCEM	Multi-agent Simulator of Competitive Electricity Markets
Power TAC	Power Trading Agent Competition
RDEG	Renewable Distributed Energy Generation
REST	Representational State Transfer
RTP	Real-Time Pricing
SG	Smart Grids
TOU	Time-of-Use
VOLL	Value of Lost Load
VPP	Virtual Power Plants
XML	Extensible Markup Language

Chapter 1

Introduction

In this chapter, a brief introduction to this work is provided. On Section 1.1, we start by giving some context about the main concepts addressed in this thesis. On Section 1.2, we talk about the motivation of this work as well as our primary goals with this thesis. On Section 1.4, we formulate some hypothesis to seek the objectives of this thesis. On Section 1.5, we explain the organisation of this document.

1.1 Context

The energy distribution is changing rapidly from a centralised scenario to a decentralised and diversified schema [Fang et al., 2012]. The emergence of cheaper and better options to produce clean and renewable energy by a regular person is being supported by new governmental policies, creating new relationships between energy demand and supply [Grijalva and Tariq, 2011].

The evolution of the 20th-century energy grid with the introduction of new information technologies and flows led to the concept of Smart Grids, evolved energy grids and related services with multiple new capabilities, such as demand-response, dynamic markets, etc. In the context of this work, we will prioritise the information flow [Fang et al., 2012] and the dynamic markets, which are relevant in the business logic layer, without bothering with more low-level problems as the ones related with energy production and distribution itself. In this context, retailers previously needed to go to each consumer's house periodically to check consumption, but nowadays, they can monitor consumption remotely at every moment through connected "smart" meters. Information flow enabled smart metering, grid balancing demand-side management and real-time monitoring [Panajotovic et al., 2011].

Smart Grids are not only changing how energy is produced and consumed, but also bringing more opportunities to the services and business that depend on the Energy Grid. New control strategies will be required as well as new markets will emerge from them [Fang et al., 2012]. These opportunities will require in-depth studies about their impact on the whole Smart Grid ecosystem since not all of them can be beneficial to the system. A new entity can enter with some new market policy that can harm the system or not provide a fail-safe mechanism. If his strategy goes wrong, the system has to be able to prevent and solve these cases [Ringler et al., 2016]. Also, as we cannot predict the new market tendencies in the future, but to observe new market structures that exist in other scenarios, we believe that simulation of these structures in the smart grids could help to understand the effect on the electrical grid. Beyond that, the capability of consuming and producing at the same time points towards a new emerging entity: the prosumer [Grijalva and Tariq, 2011]. Prosumers also have a significant impact on the way the grids work, since they can introduce more complex decisions and more dynamic behaviour.

The participation of the consumers will tend to approximate them to prosumers, by allowing them to have photovoltaic (PV) panels and other renewable small size production, as well as by using their electric vehicles (EVs) to store and inject energy to the grid soon. In the current state, consumers decisions are basically related to demand-response and the tariff problem: the first regards the behavioural changes such as turning appliances on or off to help reducing profile peaks at some time; the latter corresponds to customers choosing their tariffs (or plans) looking for a more adequate plan in terms of price and load that could imply less cost at the end of the charging period. The market should provide the infrastructure to the providers create and publish tariffs, and consumers watch for public tariffs, seeking the more adequate for their preferences. In the future, the more options are given to the consumers (and prosumers), more complex is the decision to attain one tariff or another. Therefore, it is very important to analyse the provider's strategies to create tariffs to get a high market share, assuming that dissatisfied clients tend to look for other tariffs even though it means cancelling a contract and paying cancellation fees. For the providers, this is a situation to avoid since they buy the energy from big suppliers and must guarantee the minimum amount to keep the system working. The stability of the group is essential to the providers, then, to predict the quantities to buy and even to better distribute the energy and the prices among their clients. Whenever the provider can't provide the required energy to its clients, it must buy this exceeding amount at a higher price and eventually, paying sanction fees, etc. It is extremely necessary to evaluate and analyse new market strategies and business models in order to captivate the consumer decision [Bamberger et al., 2006] in this new dynamic environment.

Different business layers can be considered when analysing energy markets. Since the definition of market goes through the virtual place where people can trade goods and services, the smart grids are also enabling new kinds of auxiliary energy markets: from new services over the energy data to new possibilities to trade energy locally or remotely. In the same direction, virtual markets research is now getting some attention. Virtual markets comprise the multiple architectures for that trading environment that are not always related to the physical infrastructure. For example, some energy companies can operate virtually by offering energy tariffs without having any physical support but paying for its usage. From the traditional operators perspective, some virtual markets could also be invisible, as in the example of the community markets. We believe that some communities could elect a representative that goes to the market as a big player, but in the inside, it can sell energy to other community participants the same role performed by the traditional providers.

Some examples of the possibilities of virtual markets are virtual power plants (where multiple power producers are seen as one) and household communities [Sousa et al., 2019]. Virtual power plants can replace a traditional power plant providing more flexibility and higher efficiency. Appealing usage of this structure is in the ability to handle electricity in peak load [Fang et al., 2012]. On the other hand, different formation mechanisms and aggregation strategies can be studied for a community market. Our literature analysis points out that given the economic impact the rise of community markets could bring to the overall smart grid panorama and the other governance issues that arise, there are few specific research in this area, even less if we consider the tariff problem and simulation for tariffs inside community markets.

In this work, we will try to understand if a community provider, the entity responsible for representing the community, that, therefore, knows its target consumers can create more suitable tariffs to them. While regular providers create generic tariffs trying to maximize profit aiming for the average consumption of a population, a community provider wants to adequate its tariffs to the group it represents, meaning to keep cohesion inside his community (same profile group) and to have the most personalized tariffs for them, assuming that it might have some knowledge the regular providers do not have access to. Also, community providers can focus on the stability of the group; it means that a cohesive group should not suffer radical or frequent leaves, meaning the estimated consumption/production should be more precise. In that sense, suitable tariffs are the ones that fit the consumer's load and lower prices and taxes.

Smart Grids studies are a necessary step towards the automation of human society since our energy dependency will only increase. Fundamentally, the evaluation of new market strategies and architectures, such as the possibility of having community markets should comprise a strict agenda towards the Smart Grids implementations and the market liberalisation it supposes. Simulation is required to evaluate the impacts of different strategies not only in the market level but also regarding the grid's capabilities and to that sense, this works aims to attack some of the problems regarding new models of energy community markets.

1.2 Motivation and Relevance

The study of virtual market scenarios is not restricted to energy markets. Any similar formation that can get insights from the energy area could benefit from our findings. Some interesting trend corresponds to the emerging characteristics of dynamic markets wherever there is some liberalization in trading, where services and goods can be traded in a high frequency than humans are available to understand and act. With this, new opportunities will appear both for clients and providers. Knowing that it is necessary to study these news tendencies to fully take advantage of specific characteristics of markets such as distribution and automation. The main motivation points of this work are:

- Traditional market tariffs are too generic: meaning that consumption profiles, as well as user size and behaviour, is not usually considered when creating a tariff. Providers try to attract as many consumers as possible and not groups or just one in particular;

- Community markets appear in the context of smart grids as a way of offering more customised tariffs. Community providers could know customers characteristics such as their average consumption, specific appliances etc, and use this information to customise tariffs for that group. Moreover, developing new provider models, specifically one that is at the same time consumer and provider could lead to new market participation models;
- Simulation systems usually don't consider the presence of community markets: millions of people worldwide use smart grids and is important to study and understand the impact of such structure in the whole grid;

1.3 Goals

These topics motivate this work, conducting our work in terms of the assumptions and hypothesis towards our goals. In this work, we want to analyse the impact of the existence of community markets over the current structures in the smart grid. From a customer perspective, we want to investigate whether the presence of tailored tariffs represents a more suitable plan making customers to change tariffs less frequently while reducing the amount spent because of imbalances. On the other hand, we want to analyse how community providers could create adequate tariffs from the ones available in the market. To evaluate what is a suitable tariff and study how to create and modify them in this context. Finally, aiming to analyse the impact of community markets on the traditional markets should also open new research opportunities regarding multi-market structures and market liberalisation in the smart grids. The ultimate goal of this work is to design and implement simulation strategies for smart grids community markets.

1.4 Hypothesis

Literature about smart srids and smart grids markets is very extensive. However, research about virtual markets and community market in this context is somehow limited. We took into account the following assumption:

> *Traditional tariffs are not always adequate for client's profile and they are constantly seeking for better alternatives even if that implies paying for contract violations*

Meaning that the client sometimes is penalised because of the market offers being too few or too inadequate. A natural consequence is to have the client trying to look for better conditions even though they must pay ending fees when leaving to new contracts. With this assumption in mind, we create two hypotheses to seek the goals of this thesis:

Hypothesis 1 (H1): *If clients with similar profiles can be seen as a community and a community provider is aware of those profiles, then it can provide more suitable tariffs*

Hypothesis 1 aims to group clients by profile, where the pattern can be a utility measure taken into consideration consumption, contract cost, chronological load utilisation, and others. Groups could represent communities of entities that do not need to be physically connected or regionally close. A community provider will manage the community by representing them on the market. For the providers, a community provider is a regular consumer, a client. But for clients, a community provider is seen as an entity that can supply energy.

Hypothesis 2 (H2): *If a community provider can buy from other providers and create and update suitable tariffs for the consumers it represents then is more likely to keep client's in the group*

Hypothesis 2 claims that with a broker representing the community, he can provide a tariff that will make the customer more satisfied. Thus decreasing the likelihood of the customer wanting to change their contract.

1.5 Document Organisation

This document contains six more chapters. On Chapter 2, some smart grid, market, tariff and agent model concepts are exposed and discussed to help the reader in fully understanding the problem that this work aims to solve. On Chapter 3, is presented the literature review containing agent-based frameworks, multi-agent systems for smart grids, smart grid simulation based on markets and a discussion about the literature gap. On Chapter 4.1, we present the methodology, system architecture and technologies used to execute this work. On Chapter 4, we explain our implementation steps. The two services created, household module and tariff module, are described, and its features are discussed. Also, agent models are revealed and explained. On Chapter 5, simulation scenarios and their configuration are explained. Additionally, results are uncovered and discussed. Finally, on Chapter 6, the main contributions of this work are revealed, a hypothesis review is done, conclusions are drawn based on the results and future work is revealed.

Chapter 2

The tariff problem and Community Providers

In this chapter, we address some important concepts regarding the tariff problem. On Section2.1 smart grid challenges and different layers are revisited. Section 2.2 presents different energy markets and their characteristics. On Section 2.3 tariffs are described and clarified to help comprehend decision models present in this work. On Section 2.5 microservices and agent modelling using a standard process modelling notation are outlined as well as their relationship with agent behaviours.

2.1 Smart Grid Challenges and Layers

The smart grid is the evolution of the 20th-century electric grid [Fang et al., 2012]. The arrival of smart grids changed the paradigm of the old electrical grid, where the power followed a one-way path, from producer to the end user. In smart grids, there is a two-way flow of information and electricity. This capability aims to create an automated, widely distributed delivery network [Wang et al., 2013]. Smart grid introduction follows a path seeking a more efficient, more reliable, more secure and greener grid [National Energy Technology Laboratory, 2007].

Communication infrastructure is an exceptionally complicated system [Yan et al., 2013]. In the next sections, we will list some challenges in smart grids presented by Ramchurn [Ramchurn et al., 2012] as well as analyse a smart grid layer vision proposed by Babic [Babic and Podobnik, 2014].

2.1.1 Reliability

A reliable energy grid provides energy without outages, consistently. However, keeping a modern grid reliable is becoming more challenging because of the introduction of a communication infrastructure [Moslehi and Kumar, 2010]. One of the core principles of smart grids is the introduction of renewable resources, making possible distributed and dynamic generation over the consistent production of the big power plants based on carbon or gas. However, predicting renewable energy generation is not easy because it depends on external factors such as wind speed or light intensity, where forecast error could be more significant than 25% [Moslehi and Kumar, 2010].

On the other side, information flow allows load management to enable services, not strictly related to the physical aspect of the grid, but more related to control that can be used in a peak-load period, congested operation or even in fault detection [Mathavi et al., 2012]. One example of a management technique is demand response, allowing the customer to lower his load consumption on certain conditions such as emergencies, or high prices during peak-load [Rahimi and Ipakchi, 2010]. With this technique, retailers shift some consumption to another period, getting a flatter load.

2.1.2 Demand-Side Management

Despite the efficiency of electric devices, energy consumption is arising every year. Although energy generation isn't a problem, grid capacity worries many people. The grid is close to the limit, and the use of Demand-Side Management (DSM) is a way to push the limit [Palensky and Dietrich, 2011]. DSM represents how a utility can intelligently influence load: a simple switch between more efficient lights or installing a sophisticated dynamic load management system. Another solution, suggested by several researchers, can be the use of a combination of more refined tariffs and "agents". One example of this can be real-time pricing (RTP) tariffs with "agents" that answer to a price signal [Schweppe et al., 1989, Ramchurn et al., 2012]. On the other hand, the use of RTP can build peaks in demand at times not foreseen, when countless consumers respond similarly, shifting consumption, and, inadvertently, synchronise with others [Ramchurn et al., 2011]. However, trust in DSM technologies will not be enough and is crucial a more refined approach [Ramchurn et al., 2012].

2.1.3 Energy Prosumers

A bidirectional flow of energy and information allows storage, demand response, and distributed renewable energy sources, allowing the appearance of consumers that also produce and store energy [Grijalva and Tariq, 2011]. With the introduction of a different actor in the environment, market entities need to adapt [Ramchurn et al., 2012]. The addition of these entities translates in more transactions in smaller amounts of energy, helping on the development of different markets [Bamberger et al., 2006]. The prosumer interacts with the external world by consuming, producing energy and participating in the market [Grijalva and Tariq, 2011]. Prosumers need to optimise both production and consumption, aiming to make trading decisions in real time.

2.1.4 Virtual Power Plants

Virtual Power Plants (VPP) represent an "Internet of energy", as Asmus [Asmus, 2010] said. A VPP represents the capacity of multiple heterogeneous distributed energy resources (DERs) representing a distributed power plant. However, the definition can vary depending on the geographical area [Asmus, 2010]. For example, in Europe, this means the aggregation from multiple wholesale renewable energy sources or Renewable Distributed Energy Generation (RDEG). But, for example in the U.S., a VPP is typically the use of critical peak pricing (CPP) and demand response (DR) that when accumulated as resources can imitate characteristics of a traditional power plant [Asmus, 2010]. A VPP can replace a typical power plant providing more flexibility and higher efficiency. Interesting usage of this structure is in the ability to provide electricity in peak load [Fang et al., 2012].

2.1.5 A Layered Approach to Smart Grids

A Smart Grid can be organised in multi-layer functional architecture, as seen in Fig. 2.1. The lower the layer, the closest to the physical world. On the other hand, higher layers are more closed to the virtual world, related to the services, markets and data the grid generates and how they can affect different dependent environments, such as electric vehicle traffic and charging management, household profiles on where and when to use some electrical appliances, etc. Overall, the Smart Grid has impacts throughout all aspects of our lives.

In the physical layer, it is possible to encounter the electrical infrastructure, consisting of power stations, high voltage transmission lines, and distribution lines. Above this layer, there is an information communication technology (ICT) layer that takes advantages of two-way communication where the main objective is to ensure performance, secure and reliable communication and control of all components of the grids [Panajotovic et al., 2011]. The ICT layer emerges with the introduction of smart grids. The top layer is the market layer, where tariffs and contracts are exchanged for electricity. The core function of a market is to balance demand with the supply of resources.

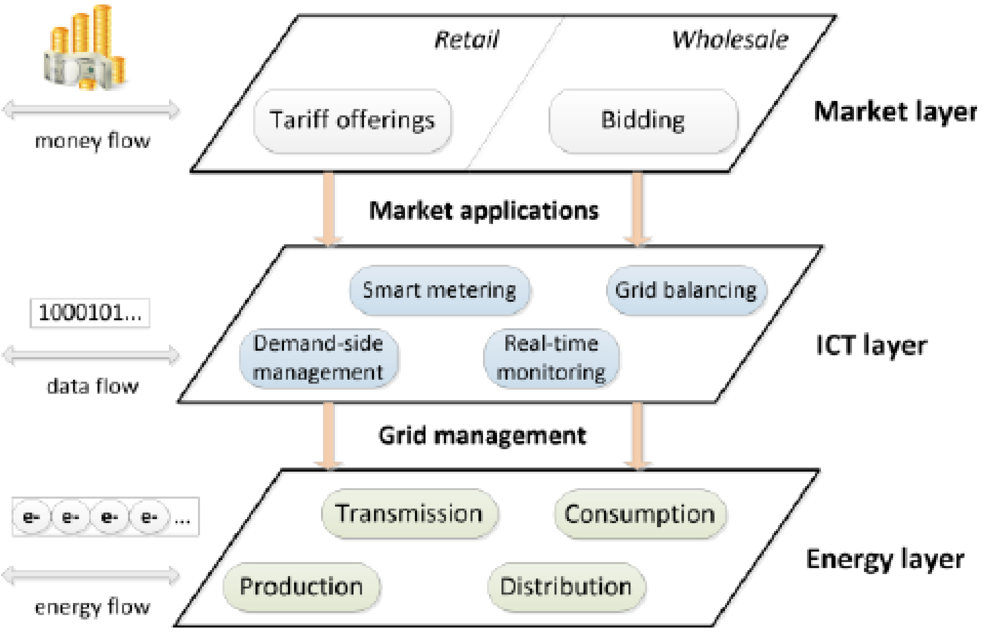


Figure 2.1: A smart grid vision in layers [David et al., 2010]

2.2 Multi-market Environments

A market is a structure where it is possible to encounter forces of demand and supply, and where buyers and sellers interact with exchanging services or goods. Rúbio [Rúbio et al., 2017] propose a different market structure approach for the Smart Grids, considering its resources, participants and the characteristics of each market analysed. In Fig. 2.2 we see how the authors depict a multi-market structure, considering the existence of markets between suppliers and providers (B2B), providers and consumers (B2C) and only between consumers (C2C).

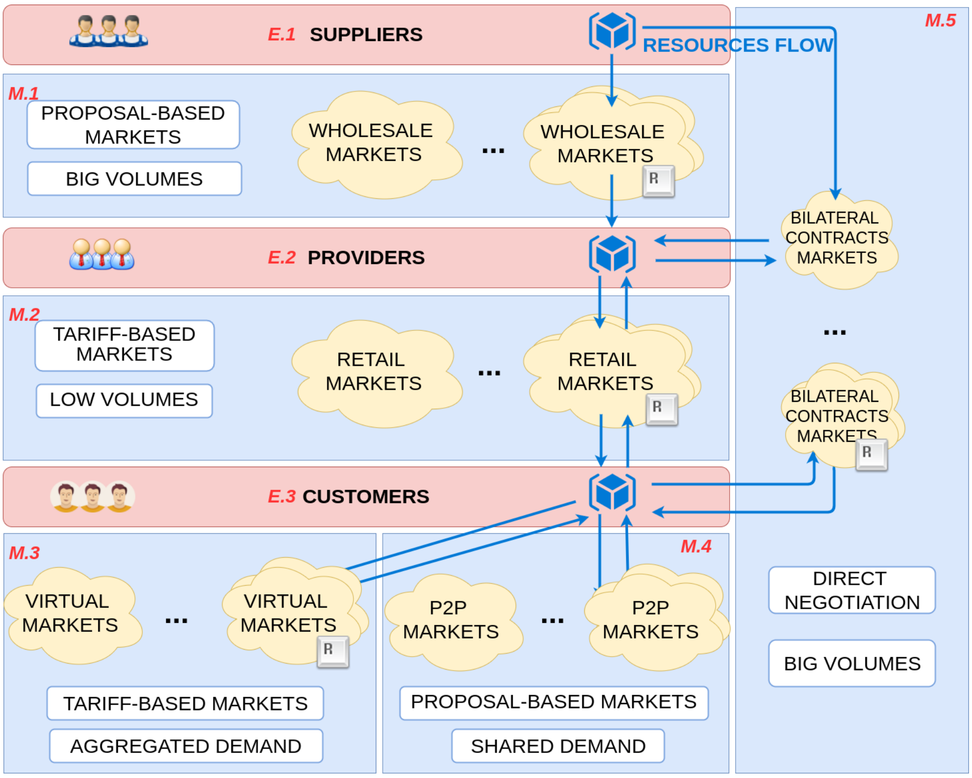


Figure 2.2: Idealisation of a market ecosystem [Rúbio et al., 2017]

Assuming their approach is the most adequate to our vision of the Smart Grids markets, it is important to explain how each market is defined and what is their composition in the Smart Grid scenario, as follows:

- Wholesale Markets: a market with interactions of suppliers and providers, mainly characterised by proposal-based markets. Multiple studies can be found about this market in the literature;

- Retail Markets: a market with interactions of providers and consumers, mainly characterised by tariff-based markets. Multiple studies can be found about this market on literature;

- Peer-to-peer Markets: a market with direct interactions between customers, very similar to a retail market but without the provider. Still an open field for study because of its context-dependency;

- Virtual Markets: a market characterised by dynamic coalitions of customers aggregated by the demand to achieve a particular goal, very similar to a retail market. A gap in the literature, where very few studies are presented;

In the next sections, we present an in-depth analysis of each market.

2.2.1 Wholesale Electricity Market

Keeping the grid stable is all about maintaining a balance between supply and demand, respecting some constraints such as generation capacity, demand elasticity, flexibility, storage, and transmission [Stoft, 2002]. These characteristics complete electricity markets configuration that contains different sub-markets with secondary functions such as offer various trading opportunities and allocate resources. To better understand the electricity market, in Europe the market consists of an intraday market, a balancing market, a day-ahead spot market, and an imbalance settlement [Scharff, 2015].

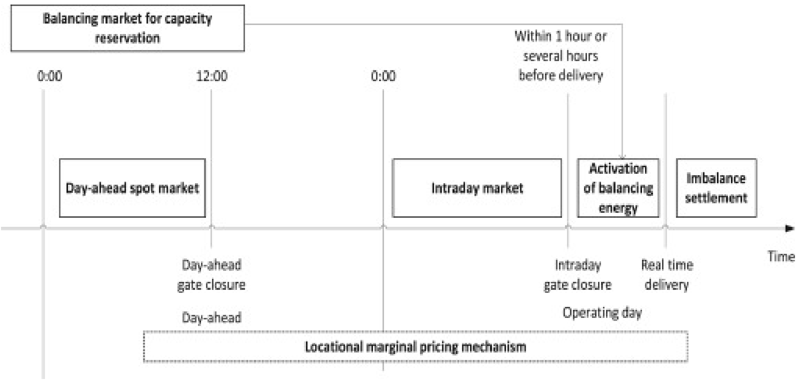


Figure 2.3: Europe electricity market [Scharff, 2015]

The *day-ahead spot* market is a contract between buyers and sellers to trade hourly electricity products for the next day in the wholesale market. If all the demand is not suppressed due to, for example, generation problems the spot price is called scarcity price [Hu et al., 2018]. This price is usually set at the value of lost load (VOLL), which defines the value attributed by the consumes to unprovided energy. On the other hand, *intra-day* market allows securing the balance between supply and demand, as a supplement to the day-ahead market. This trade takes place short times before delivery. This market offers flexibility to participants, reducing the need for more expensive resources [Scharff and Amelin, 2016]. This type of market can be based on continuous trading or discrete auctions, depending on the country. Also, the *balancing market* is the last barrier to balance demand and supply before the delivery time. Finally, the *imbalance settlement* is the market responsible for balancing the system. Prices are determined each half an hour and are extremely higher when compared to the other markets mentioned above. In some countries from Europe the total value also contains a multiplicative or additive punitive component [Vandezande et al., 2009].

2.2.2 Retail Electricity Market

Electricity bought from the wholesale market is sold in the retail electricity market to the end consumer by supplying contracts. These contracts usually contain a price, an energy source, contract length, and other variables [Yang, 2014] and the clients may choose to subscribe from different offers, called *tariffs*. The price defined in the contract can be set as an average annual cost or, more recently, through demand response (explained in section 2.1.1) making the price dynamic. With the retail electricity market becoming a decentralised one, consumers are supposed to choose a retail energy supplier. The option of which retail to choose can be from a combination of price/service quality that best meets their needs. In the other site, retailers competing with each other are supposed to offer an enhanced group of service products like risk and demand management [Joskow, 2008].

2.2.3 A specific case of Virtual Markets: Community Markets

In the context of the Virtual Market, different structures have already been studied as the virtual aggregation of clients that trade between them. For example, the P2P market is highly studied in other areas, such as logistics and e-commerce. In the smart grids, P2P markets have mostly been studied in terms of how to provide energy and share demand between household profiles. On the other hand, little has been studied regarding the Community Markets. For us, a community market is a composition of customers that have a similar profile (as per similar location or similar constitution, such as small household profiles with same number of family members and same apartment configuration, or on the other way, big department stores that share the same building could be good examples of virtual market participants). Depending on the configuration, some participant is elected or created (virtually) to represent the community. We will not enter to that detail since it is out of the scope of this work and just the study of how to elect one member could be a theme for another thesis. This representative, called community manager has a dual role: first, from the providers perspective, it is seen as a single customer with significant energy needs. That fact could enable it to access cheaper tariffs for such type of consumption; secondly, the other community members can now see it as a provider. In this sense, the community manager can create de-regulated tariffs and make them available to its subscribers. The community manager is responsible for managing all inner market activities of the community as well as intermediate all interactions with entities outside the community [Sousa et al., 2019], as shown in Fig. 2.4.

This market idealisation can be used in other cases like a group of neighbouring prosumers [Verschae et al., 2016] or to microgrids [Akter et al., 2016]. More broadly, community members need to share common goals, similar profiles, activities and interests. Community members do not

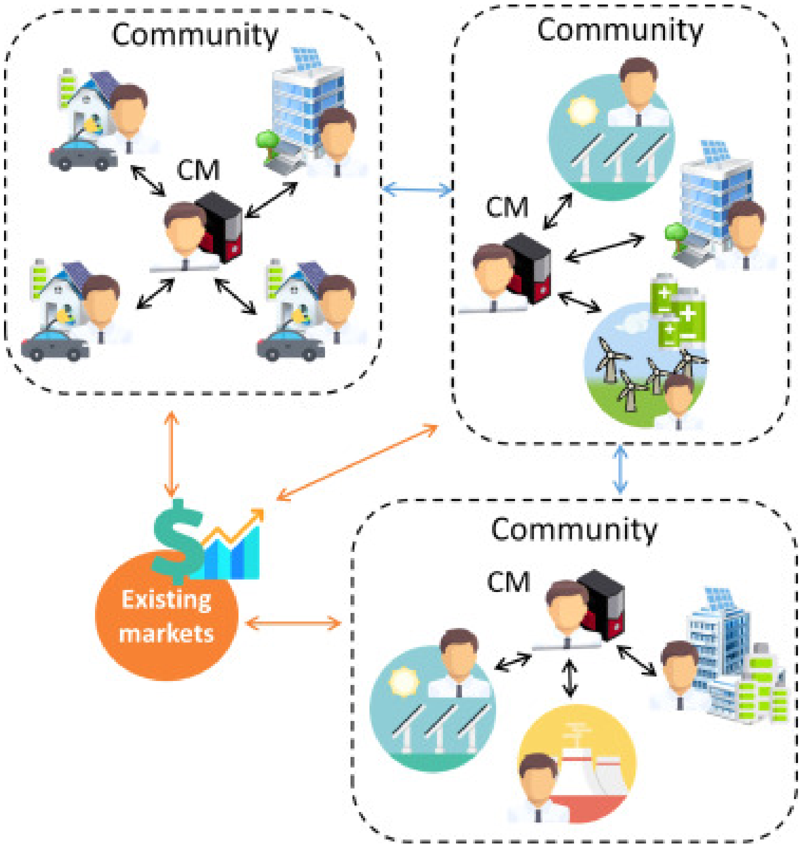


Figure 2.4: Community-based market design [Sousa et al., 2019]

need to be in the same location. Sousa [Sousa et al., 2019] expose two different scenarios formulated from other authors: a "community-based market with prosumers working in a collaborative manner" [Moret and Pinson, 2018] and "multi-class energy management of a community-based market" [Morstyn and McCulloch, 2018].

2.3 Tariff Definition

Markets usually deal with prices for goods or services and entities that want to trade them. In our study regarding virtual markets, the need for a tariff definition arises from the moment the community manager needs to buy and offer energy for its customers. Thus, it is necessary to understand the concept of a tariff.

Tariff plans and tariff prices do not have a common definition: they differ widely from country to country. External factors have an impact like the price of generation, local weather patterns, transmission and distribution infrastructure, among others [U.S Energy Information Administration, 2008]. Utilities generally divide clients into three groups: residential, commercial and industrial. Tariff rates in these groups vary. This separation happens because of the load size and usage profile. Load size is the consumption of a customer. Residential consumers usually have low voltage usage.

In comparison, industrial consumers have high voltage usage. Low voltage usage has more expensive rates than high voltage usage. High voltage is cheaper because high voltage transmission is a lot more efficient compared to low voltage transmission. The other group separator factor is usage profile. This factor can be divided into time-of-use(TOU) and load factor. TOU rates are characterised by fixed electricity prices that vary based on the time of day and week. Load factor is defined as the average load divided by the peak load in a specified period [Watkins, 1915]. Utilities use different rate structures [Borenstein, 2007]. Being them:

- Fixed: in this schema, the clients pay a fixed value per kWh.

- Tiered: tariff rate changes depending on client usage. If the rate rises or drops depends on the provider goal. For example, if the goal is to save energy, the rate rises. Or, if the goal is to maximise profit, the rate drops slightly;

- Time-of-Use(TOU): tariff rate changes depending on the time of day. This schema is called the multi-time schema. Can be a day-night structure, can vary hourly, among others;

- Demand rate: tariff rate changes depending on the demand for energy. This rate schema is an example to implement demand-side management;

- Tiered within TOU: tariff rates vary depending on the amount consumed and the time of day. This schema is a merge of tiered and TOU schemas;

Although consumers are free to choose between one of these schemas, tariffs can also include fees and periodic payments. Fees for subscribing a new tariff or unsubscribing early [Cory et al., 2009]. Periodic payments for the counter rental and other taxes.

2.4 Agent and MAS

An agent can be defined as a computer entity that can make autonomous decisions and act in its environment to achieve its own goals [Shen and Norrie, 1999]. Agents can also interact with others by sharing data and by engaging in interaction activities like cooperation, coordination, and negotiation [Shen and Norrie, 1999]. When multiple agents share the same environment and interact, we call that system a Multi-Agent System (MAS). MASs also encompasses the domain of agent-based control systems and (distributed) artificial intelligence [Shen and Norrie, 1999]. MAS is different from Agent-Based-Model (ABM), while MAS tries to solve specific engineering problems in Complex Adaptive Systems (CAS), ABM aims in finding analytical insights typically in natural systems of the collective behaviour of agents [Niazi and Hussain, 2011].

2.5 Microservices and Agent Modelling Using BPMN

In Chapter 3, we will present a more in-depth analysis of how multi-agent systems and agent-based simulation could be a good approach for representing the related entities in the smart grid. By now it is essential to understand that although multiple tools have already been presented in the last years, very few of them deal with the multi-layer architecture of the smart grids markets and even fewer concern virtual markets. In this sense, some possibilities were discussed in the context of this project: 1) to adapt some simulation tool to perform our analysis; 2) to develop a simulation tool that would be flexible enough for a more generic smart grid approach in the future. We have opted for the second mostly because of the expertise of the authors regarding distributed agent-based simulation, a natural strategy when entities are autonomous, and decisions must be performed in an agent-level.

In this context, the Agent Process Modelling (APM) seems to be an exciting methodology [Rúbio et al., 2019], since the agent behaviours are modelled through process models and the capabilities as services, leading to the flexibility we wanted, either in the theoretical and the practical aspects. APM aims to forecast how a particular set of actions must/should/could be done, instead of what the process itself, which is what happens. Business Process Modelling Notation (BPMN) is used to represent processes since it is a standard notation for that purpose. BPMN is a graphical representation of business processes as, for example, Unified Modelling Language (UML) is for visualising the design of a system. Agent capabilities are divided into services.

Microservices, the de facto approach for distributed web-services are perhaps the adequate systems to represent those capabilities. Still, few works are trying to bridge the gap between microservices and multi-agent systems. In this sense, the APM methodology could bring more flexibility to simulation systems since the agent capabilities can be changed without changing the processes. The business process models work as the orchestration platform for the microservices, composing the agent behaviours.

Microservices are a software architecture pattern where an application is a collection of loosely coupled services that are organised around business capabilities. In this architecture (Fig.2.5), services are characterised by their heterogeneity and are independently deployable. These properties allow this software architecture to be highly scalable [Richardson, 2014].

The main advantage of using this new agent-process architecture instead of traditional agent frameworks is that this way allows for the model to be understood by anyone with knowledge about BPMN [Onggo, 2012]. BPMN supports multiple diagrams which include: collaboration diagram, process diagram, conversation diagram, and choreography diagram. Fig. 2.6 shows BPMN element categories divided in five categories: connecting objects, flow objects, data, artefacts and swim-lanes. Connecting objects and flow objects are used to construe the behaviour and structure of a process. Connecting objects can be used to connect the flow of objects between them or with other elements. To understand more about BPMN core elements and their specification we suggest you on check Object management group (OMG), the entity responsible for controlling BPMN.

In support of the APM methodology, the literature regarding agent-based software and BPMN

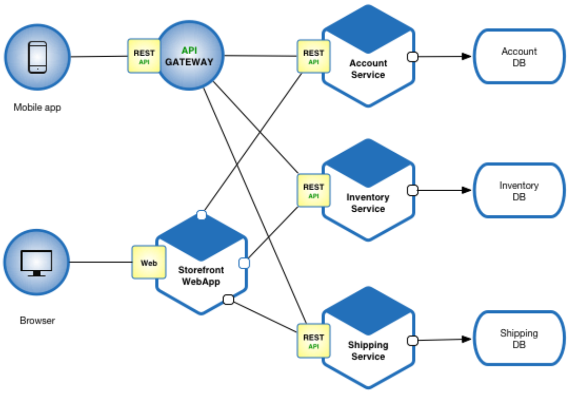
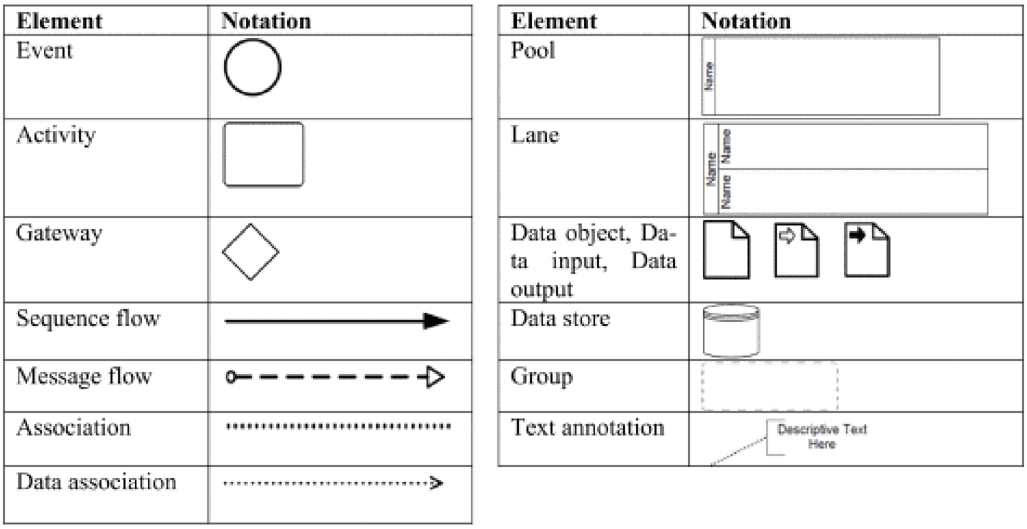


Figure 2.5: Microservice architecture example [Richardson, 2014]

have already been looking for some agent-process coordination in a while. Some authors showed that the most critical issues in agent-process modelling are the agent behaviours, interactions and the environment representation [Onggo, 2012]. The most relevant aspect to consider is the behavioural modelling; it means BPMN could help representing the collaboration between agents (*inter-agent* model) or either the protocol for the agent itself (*intra-agent* model). In the first, BPMN diagrams are usually used to represent the interactions of multiple participants that belong to different elements, such as pools or lanes. By consequence, it has been shown that going from inter-agent models to the development of the whole system is a difficult task. Therefore, the path for intra-agent modelling is still an open issue and lead the way, so our research can benefit from modelling agent behaviours in the smart grids. Moreover, the development of mature and scalable BPM engines (capable of interpreting and instantiating processes from BPMN) have also opened the possibility to create an agent-process entity (as in APM) that executes agent behaviours by running on top of such technologies.

In the intra-agent models, we use the process model to represent the internal agent decisions, and task flows accordingly to the run-time variables (agent knowledge). Some advantages are clear visual boundaries or the ability to reconfigure the agent process graphically, making it reducing the effort cost between the design and deployment of agent systems. Agent autonomy is represented as an event-based manner, by BPMN events. Different agent decisions can be designated with BPMN gateway. Complex agent behaviours are possible to use a combination of connecting objects and flow objects. Finally, Bhakti S. S. Onggo [Onggo, 2012], concludes in its work that although BPMN was designed for process-oriented modelling language, it is possible to use BPMN to model agents. Fig. 2.7 shows an example of a pattern generic agent suggested by the author.



Element	Notation
Event	
Activity	
Gateway	
Sequence flow	
Message flow	
Association	
Data association	

Element	Notation
Pool	Name
Lane	Name Name Name
Data object, Data input, Data output	
Data store	
Group	
Text annotation	Descriptive Text Here

Figure 2.6: BPMN core graphical components [Chinosi and Trombetta, 2012]

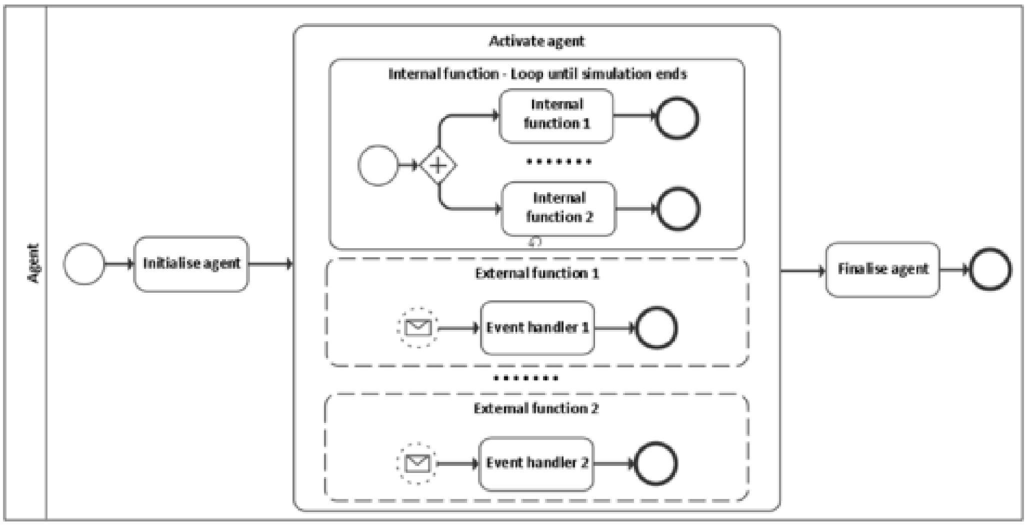


Figure 2.7: BPMN pattern for a generic agent [Onggo, 2012]

In this chapter, we have presented the scope of this work, as well as some central concepts and how they are related to each other. In Chapter3, we will further discuss the literature gaps and the opportunities regarding agent-based models for Smart Grid communities.

Chapter 3

Literature Review

In this chapter, a literature review is performed. On Section 3.1 multi-agent systems for smart grids are outlined. Section 3.2 discusses market-based simulation on smart grids. Finally, a gap in the literature about the problem this work aims to solve is presented in Section 3.3.

3.1 Multi-Agent Systems and Smart Grids

Electricity systems can be examined as complex adaptive systems [Holland, 2006] or systems-of-systems [Maier, 1998] with the help of autonomous agents. As introduced in Section 2.1.5, electricity systems could be seen as a compound of several layers. Focusing on the market layer, the relationship between markets and the interactions between their participants, the possibility of modelling agents that have complex behaviours inside those markets could be useful in different research scenarios. Besides of markets *per se*, contracts, tariffs and negotiation protocols have already been studied as well as the entities present in those markets, such as producers, consumers, prosumers, grid operators, market operators, and other intermediaries [Ringler et al., 2016]. In its work, Gnansounou, E. et al. [Gnansounou et al., 2007] have explained that from a domain standpoint, it is possible to notice two different types of agents: synthetic agents and basic agents. A *basic agent* is characterised by a group of dynamic and static attributes and some skills related to computation, reasoning, and communication. Thus, a *synthetic agent* is characterised by the ability to manage, control and coordinate a group of basic agents accordingly to its distinct strategies.

The work in [Gnansounou et al., 2007] summarises other similar research regarding the energy entities that can be represented with multi-agent systems. They considered as entities: producer or generator (G), consumer (C), distributor (D), transmission system operator (O), trader/broker or wholesaler (W), market operator (M), regulator (T) and retailer (R). The assumption is that for a given market, there is only one regulator. Synthetic agents exist to represent a market participant that collects more than the basic role, for example, a distributor that is simultaneously a retailer. Figure 3.1 shows a possible MAS architecture for electricity markets.

Gnansounou [Gnansounou et al., 2007], considered a spot market when proposing this architecture. A spot market is characterised by the immediate delivery of the exchanged resources. In

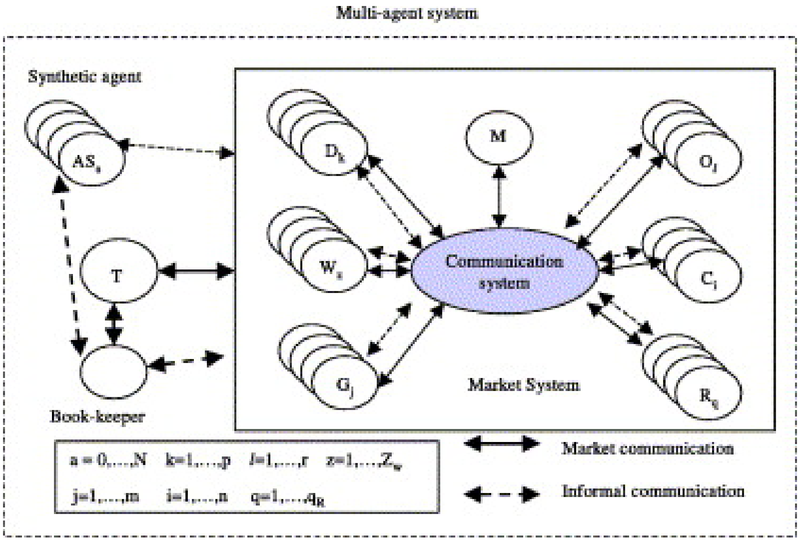


Figure 3.1: MAS architecture for electricity market [Gnansounou et al., 2007]

this example, there are coordination dialogues among market operators, consumers and energy producers. This market is managed by the market operator. Transactions are agreed through auctions, where a deal should lead to physical exchanges. Each consumer needs to inform the market operator the amount required, in the day before the sale. As well as, each producer informs the market operator, about his conditions (price and quantities) the day before the auction. After that, a schedule is built based on the prices of the offers. Then a production curve is made accordingly to the schedule to meet the demand. Demands are established as periods of 24 hours. In each period, the market operator increases price orders with all tenders until all demand of a period is fulfilled.

On the application side, Multi-agent systems can have multiple applications on smart grids. Malin and Lehtonen [Malik and Lehtonen, 2016] suggest some usages: control of microgrid using agents, fault management and self-healing of power system using agents, agent-based architecture for demand-side management, domestic load agent to optimise energy usage, smart grid network management using agents, voltage control and frequency control.

3.2 Market-Based Simulation of Smart Grids

Most smart grid simulation tools are focused on the physical layer, comprising electricity transmission and distribution simulation [Chassin et al., 2014]. Nevertheless, few simulation tools for market simulation have already been presented. The most relevant two are the PowerTAC framework and the MASCEM simulator, which will be discussed in the next paragraphs.

The Power Trading Agent Competition (PowerTAC) is both an open tournament where participants build autonomous broker agents that compete between them and a simulation tool centred in the retail and the wholesale power markets and operation [Ketter et al., 2013]. PowerTAC addresses essential elements of the smart grid challenges defined by Sarvapali [Ramchurn et al., 2012], mostly problems that affect a large number of actors with economically motivated decisions. This tool can be used to test different tariff generation policies and mechanisms to be implemented in the negotiation parts of the markets. The goal of the simulation in PowerTAC is to help policymakers create mechanisms for brokering in a high trade manner, to provide the best tariff updating policies to achieve the most significant market share and analyse the how the tariffs should affect the market and consumers. PowerTAC can provide a validation tool for new intelligent automation technologies that can support effective management of participants, but indeed, there is no way to analyse other market structures, such as the community markets and neither the possibility to observe customer behaviour change, since the models currently implemented are statistical. Main entities considered are producers, markets, brokers and clients (prosumers). It also uses environmental conditions for the variability in power production and consumption.

Multi-agent Simulator of Competitive Electricity Markets (MASCEM) is another modelling and simulation tool for studying electricity markets operation. The MASCEM multi-agent model contains players with strategies for bid definition, acting in balancing, day-ahead, and forward markets and they can use complex and simple bids. The main MASCEM goal is to experiment and simulate with virtual power plants in the wholesale markets with as many market players as possible [Vale et al., 2011].

Tool	VPP	Wholesale mrkt	Retail mrkt	Virtual mrkt	Agent learning	Brokering
Power TAC			x		x	x
MASCEM	x	x			x	x

In the previous table, it is possible to compare the functionalities of the presented simulation tools, Power TAC and MASCEM. Power TAC is a competition and ends up with a greater focus on the retail market, especially in creating tariffs to attract consumers by using agent learning to improve their strategy throughout the simulation. In the case of the MASCEM tool, the focus is on the wholesale market with the presence of virtual power plants. In this tool, the strategies are more focused on the consumption forecast with the aid of the virtual power plants. In this tool, agents also learn from the simulation. In the buyer's case to improve their bids and in the seller's case to improve the selling strategies (determined, anxious, moderated, ...).

However, both tools do not seem to predict simulation in a market with the architecture of virtual markets. Which predicts that to test these work hypotheses, a simulation environment needs to be developed.

3.3 Gap Analysis Discussion

Although current Smart Grid literature is extensive, there are only a few papers that addressed the topic of community markets, as summarised in [Sousa et al., 2019]. In this kind of markets, the idea is to consider a group of agents as a community among the whole population. This clustering could be related to the physical location, similar characteristics, shared goals and interests, etc..

Every community is represented by one or more community managers, the intermediary entity between traditional providers and the community members. Nevertheless, community markets are an emerging field in multiple application scenarios, and their study in the context of Smart Grids could also be useful for any other resource-based market application.

From a technological architecture perspective, although many simulation tools have been presented for the smart grids, none is too complete or too flexible as required to study the community markets. We have analysed the PowerTAC, and the MASCEM frameworks and however, both of them addressed different problems in Smart Grids markets related basically to the tariff problem: creating, updating and deploying exciting tariffs for its customers.

The gap in our analysis is presented as the lack of studies on how a community provider could provide better tariffs on behalf of its community members as well as the impact of assessing more suitable tariffs from its providers. One research question that arises is how community providers could attract the interest of customers to gather better conditions when performing the role of a client of big tariffs. We hypothesize that it can provide better tariffs to its customers because it knows some community members characteristics that a traditional provider does not. In Figure 3.2, a market architecture is shown. From a traditional provider perspective, the community provider is just one more customer, but from its customers, it is another provider. This duality in the community manager behaviour is a fascinating research field.

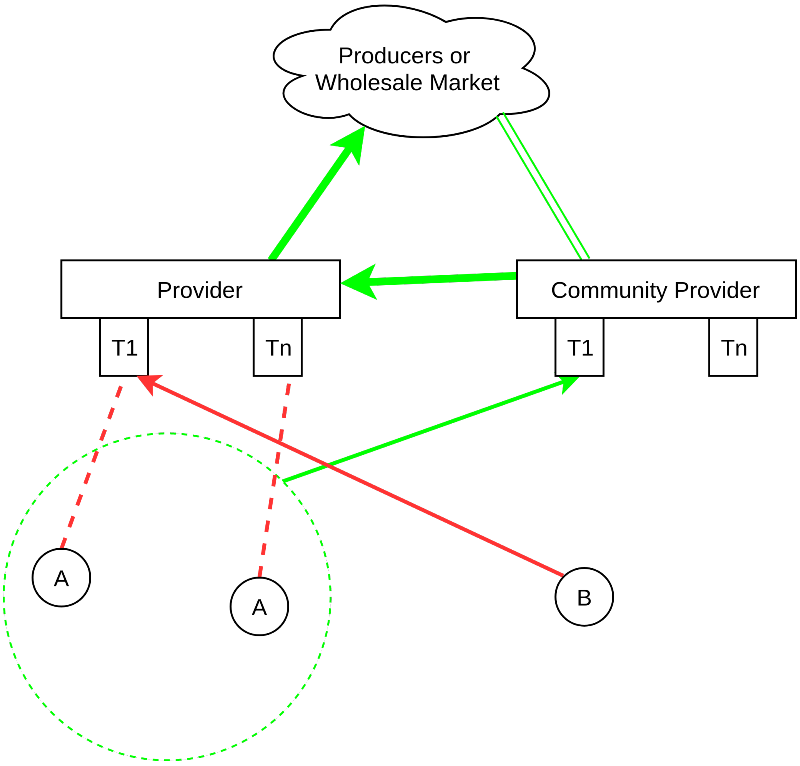


Figure 3.2: Community market architecture

As referred in Section 1.3 our goal is to study community markets in Smart Grids to fill this gap and provide insights about this environment with the development of a simulation tool.

Chapter 4

An Agent-Process Model Approach

In this chapter, the implementation of the solution is shown. On Section 4.1 solution methodology and architecture are presented. On Section 4.2 a tariff model is shown. On Section 4.3, the provider module is displayed and tariff update explained. On Section 4.4 household module is displayed and main features explained. On Section 4.5 agent process modelling service is also displayed and main features discussed. On Section 4.6 charts are shown with the main integration between services.

4.1 Solution Methodology and Architecture

4.1.1 Methodology

In order to understand the role of a community provider in a community market and if he can provider more suitable tariffs, the following methodology was followed:

1. Analyse and model agent behaviour
2. Develop agent capabilities (consumption simulation, tariff choice and update)
3. Evaluate agent performance under different scenarios

On the first step, an analysis was made of the entities present in the SG's that are relevant to the problem. After the analysis, processes were modelled trying to replicate their behaviour. The processes of the modeled agents can be found in the sections 4.5.3.1, 4.5.3.2 and 4.5.3.3. On the second step, agent capabilities were developed. These capabilities can be grouped by consumption simulation and tariff choice for consumers and tariff update for regular and community providers. On the third step, two simulation scenarios were executed and agent performance evaluated. Experiments results can be found on chapter 5.

With this methodology, the consumer agent was the first to be studied. We tried to understand which points to model. After an analysis it was concluded that it would be necessary to simulate its consumption. For this, a consumption simulation module was developed. This module is called

Household module. The purpose of this module is to represent the consumer in the system of simulation to be developed.

After the consuming agent, the provider agent was next to be studied and analyzed. This agent needed a decision model regarding their tariff update. To this end, a module entitled tariff module has been developed which contains the ability of this agent to update its fare.

Finally, the community provider agent was studied and analyzed. This agent should buy energy from regular providers and sell to members of their community. This functionality was not implemented as the community provider was a provider with a different tariff update. The tariff module also contains this decision model.

After studying and analyzing the different agents present, they were all modeled using the APM platform. This platform allows agents to be modeled on the form of processes and after their capabilities implemented in services external to the platform. In this case, the external services are Household and Tariff module.

Finally, two different simulation scenarios were used to evaluate agent performance. During the simulations were taken metrics of each agent, to be able to evaluate and draw conclusions.

4.1.2 Overall Architecture

To get a solution to this problem a multi-agent system (MAS) was used to build a simulation environment. A MAS is composed of multiple intelligent agents interacting with each other. MAS is characterized by agent autonomy (self-aware), local views (no agent has a global view of the system and decentralization (no agent is assigned to control the system). With these properties in mind, it is easy to understand the reason why a MAS was used to model the smart grid environment and its entities

This work used a distributed simulation environment, using microservices. Microservices because of its scalability, the possibility to organized them by business capabilities and for being loosely coupled.

Figure 4.1 depicts the system architecture. Three services are used. This division was made by entities and functionalities. The Household module is a service with consumers capacities. It has two main functions. Simulate consumers load consumption and tariff choice. The tariff module is a service with providers capacities. It has two main functions. Tariff assignment and tariff update.

The Agent Process Modelling (APM) module represents the simulation service. It has two main functions. Modelling agent processes and simulate different scenarios. In this platform we modelled our three different entities: consumers, providers and community providers. Then, the different simulation scenarios are tested. Representational State Transfer (REST) is a software architecture style used to define web services [Fielding, 2000]. A set of stateless operations can be used to manipulate textual representations of web resources. All services expose a public REST API. This API's can be used to services communicate between them.

From these three modules, the APM module is an external framework developed by the co-supervisor of this thesis. The household and tariff module was developed during the execution of this work.

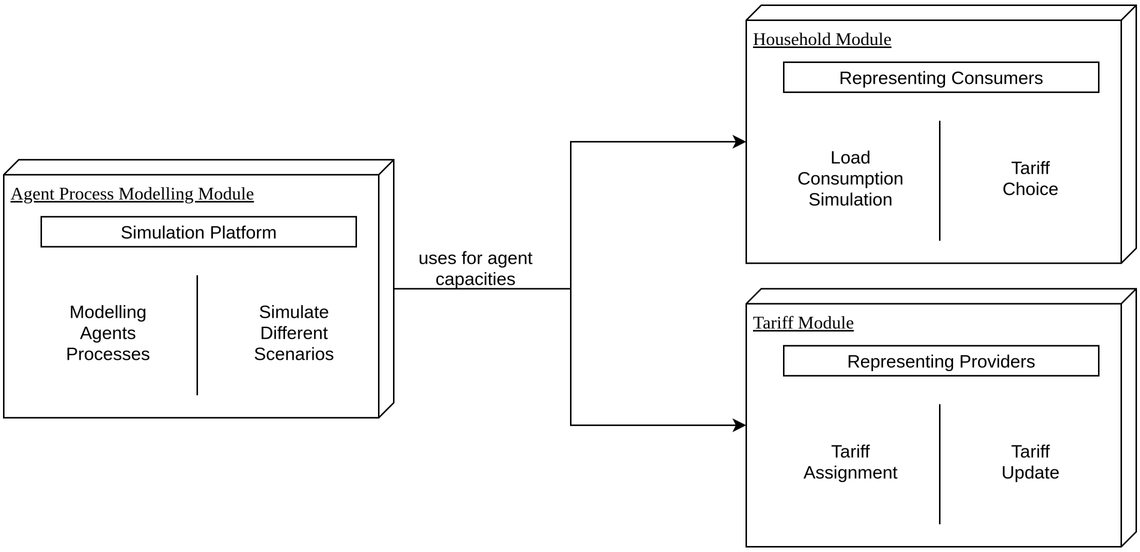


Figure 4.1: System architecture

4.1.3 Technologies Used

The Household module was implemented using Jhispter[1]. This framework is a development platform to build Java Spring Boot [2] web applications and spring microservices. With minimal configuration, we get a running application ready to start developing. Our API contains the logic to simulate consumers consumption and tariff choice. To showcase data present in the API, we have a simple front-end implemented in AngularJS[3]. To persist data we use PostgreSQL[4], a relational database. Elastic search[5] is used which adds search capabilities on top of our database. And Kafka[6], a popular publish-subscribe messaging system, is used to agent exchange message inside the service. The provider's service was developed using ExpressJS[7]. This technology is a minimal and flexible NodeJS[8] web application framework that provides a set of HTTP utility methods and middleware to quickly create robust API's. This service contains all the provider's capabilities defined in their process.

4.2 Tariff Model

This work is based on the electricity tariff. Therefore, it was necessary to model the tariff for providers and consumers to exchange goods.

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[1] More information available online at `https://www.jhipster.tech/`

[2] More information available online at `https://spring.io/`

[3] More information available online at `https://angularjs.org/`

[4] More information available online at `https://www.postgresql.org/`

[5] More information available online at `https://www.elastic.co/`

[6] More information available online at `https://kafka.apache.org/`

[7] More information available online at `https://expressjs.com/`

[8] More information available online at `https://nodejs.org/en/`

The results of our simulation are extremely independent on the tariff model used. In equation 4.1, we present the formalization of our model.

$$Tariff = <d, eWP, pP, sUF, r, t> \tag{4.1}$$

So a tariff is represented by a duration, an early withdrawal payment, a periodic payment, a sign up fee, a rate and a threshold. Next follows a small explanation about each one of the parameters:

- d → duration: indicates the loyalty period on which a subscriber needs to be with the tariff after subscribing it
- eWP → early withdrawal payment: if a consumer wants to unsubscribe from a tariff before the end of his loyalty period, a fee needs to be paid. This field contains the value to be paid
- pP → periodic payment: this is a fixed fee, representing the energy counter. This value will be used when calculating the periodic tariff cost
- sUF → sign up fee: this is a fee that needs to be paid to the provider by the entity that subscribes the tariff
- r → rate: corresponds to the value in monetary units per kWh. This value will be used when calculating the periodic tariff cost
- t → threshold: contracted power, this means that someone who subscribes the tariff cannot spend more power than the value here indicated

Electricity is a quantitative good and not a qualitative good. Meaning this that the electricity from provider A is equal to the electricity from provider B. Knowing this, we needed a tariff model capable of attracting consumers. With the introduction of these parameters, a consumer is able to easily compare tariffs and choose the most appropriate.

This model provides tariffs with a fixed rate. However, it will be simple to generalize to a function to implement the different models explained in the Chapter 1.1.

4.3 Providers Simulation

This service was created with the aim of holding providers capacities and agent creation. In our simulation, a provider supplies electricity providing a tariff. Providers periodically update their tariff to meet their objectives. This work has two different providers, a regular provider and a community provider. Both will be further explained in the next section. For now, let's focus on their goals. A regular provider wants to grow is market share and community provider wants to keep clients that fit at a given load level. Both updates will be addressed in subsection 4.3.1.

4.3.1 Tariff Update

Both the regular provider and the community provider update uses function 4.2 and 4.2. These functions receive the value to be updated and a factor. Then increase or decrease value depending on the function. Rates and fees are updated. There are minimum and maximum values for each updated parameter. If, in any update, the new value exceeds the defined interval the maximum/minimum allowed value will be used.

$$f(v,f) = v + v * f \tag{4.2}$$

$$f(v,f) = v - v * f \tag{4.3}$$

Formulas 4.2 and 4.3 are functions to increment or decrement a value. Receives two values, v corresponding to the current value and **f** corresponding to a factor, this is a value between 0 and 1.

In the tariff update we tried to model the traditional behavior of the market in which to attract more customers the supplier drops prices, when already has a certain number of customers the provider slightly increases the price. For this, price increase/decrease factors were used. These factors were set manually, but could then be the subject of a learning process to adjust these factors dynamically to market behavior.

4.3.1.1 Regular Provider

A provider has two goals: maximize profit and total market share. For the update tariff process, five variables are received. Market share, representing the percentage of clients currently using the tariff. Current tariff profit, representing the current tariff profit. Old tariff profit, representing the profit of the tariff before the current one. Current tariff losses, representing the number of clients that unsubscribed from the tariff. Old tariff losses, representing the number of clients that unsubscribed from the tariff before the current one. Then the provider updates the tariff following one of these four possible processes.

- if current tariff profit >= old tariff profit and current tariff losses < old tariff losses: this case means that the current tariff is having more adherence. Therefore, the rate of the tariff is updated. To update the rate of the tariff a factor is calculated. This factor is a random between 0.02 and 0.05 multiplied by the market share. Then, using the function 4.2 the new rate is calculated

- if current tariff profit >= old tariff profit and current tariff losses >= old tariff losses: this case means that the tariff is having a higher profit, however has customers leaving the contract. In this case the rate of the tariff and the early withdraw fee are updated. To update the rate of the tariff a factor is calculated. This factor is a random between 0 and 0.01 multiplied by the market share. To update the early withdraw fee a factor is also calculated. This factor is a random between 0.05 and 0.1. For both variables, the function 4.2 is used to calculate the new values

- if current tariff profit <= old tariff profit and current tariff losses > old tariff losses: this case means that the tariff had less adhesion and profit. Therefore, the tariff rate and the early withdraw fee are updated. To update the rate a factor is calculated. This factor is a random between 0.01 and 0.03 multiplied by the market share. Also a factor is calculated to update the early withdraw fee. This factor is a random between 0.05 and 0.1. Then, to get the new rate function 4.3 is used. And to get the early withdraw fee function 4.2 is used
- if current tariff profit <= old tariff profit and current tariff losses <= old tariff losses: this case means less profit but more cohesion. Therefore, the tariff rate and sign up fee are updated. To update the rate a factor is calculated. This factor is a random between 0.01 and 0.03 multiplied by the market share. Also a factor is calculated to update the sign up fee. This factor is a random between 0.05 and 0.1. Then, to get the new rate function 4.2 is used. And to get the new sign up fee function 4.3 is used.

4.3.1.2 Community Provider

A community provider has two goals. Maximize profit and target market share. Also, this provider wants to keep cohesion inside the community. Therefore, the update is done to meet the needs of the community members. Thus, the update is divided into two different parts. A first one updating fees and rates. And a second one updating the load threshold.

In order to update the tariff four variables are received. Target market share, representing the percentage of target clients currently using the tariff. Current tariff losses, representing the number of target clients that unsubscribed from the tariff. Old tariff losses, representing the number of target clients that unsubscribed from the tariff before the current one. Then the community provider updates the tariff following one of these four possible processes. Group load, representing the average load of the community. The first update process is:

- if current tariff target losses > old tariff target losses: this case means that the tariff had less adhesion. Therefore, the tariff rate and the early withdraw fee are updated. To update the rate a factor is calculated. This factor is a random between 0.01 and 0.03 multiplied by the target market share. Also, a factor is calculated to update the early withdraw fee. This factor is a random between 0.05 and 0.1. Then, to get the new rate function 4.3 is used. And to get the new early withdraw fee function 4.2 is used.
- if current tariff target losses <= old tariff target losses: this case means that the tariff had a bigger adhesion, improving community cohesion. Therefore, only the tariff rate will be updated. To update the rate a factor is calculated. This factor is a random between 0.01 and 0.03 multiplied by the target market share. Then, to get the new rate function 4.2 is used.

The second update process updates the threshold value using the group load variable. Function 4.2 is used, using group load as the value and a factor. This factor is a random between 0.03 and 0.05. The threshold update is done in order to meet the community consumption levels. In this way, community members get a more appropriate tariff for their needs.

4.4 Household Simulation

A consumer is an entity that demand electricity from the grid and to have the required availability must pay for its use. In order to understand the consumer behaviour regarding load consumption and also tariff changes, our idea is to develop an agent simulation model able to change its consumption according to tariff stimuli. The classical approach of consumer consumption representation in other simulation tools is in the form of a function (Fig. 4.2).

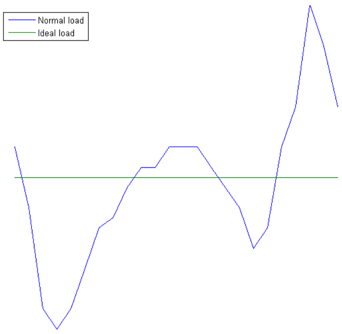

Figure 4.2: Example load function

We opted for the household simulation where houses have different appliances. Each appliance has its schedule of execution. Adding the load of all the appliances we get the load of the house. The consumption of an appliance is not constant and varies according to its execution, using the load function to represent its consumption, it is possible to obtain a representation closer to reality. This being the advantage compared to the classical approach.

In order to simulate houses with consumption, entities were created. The relation between these entities is shown in Fig. 4.3.

The environment entity represents initial parameters and current state of the simulation. This is a singleton entity. The environment contains the following fields: current tick of simulation, time unit, initial date and scheduler rate. The current tick of simulation corresponds to the current time in the simulation. Time unit constant which translates the number of minutes corresponding to a tick. Initial date of simulation in YYYY-MM-DD HH:mm:ss format, with this field plus the number of ticks and time unit we can get simulation date at a given moment. Scheduler rate which corresponds to the interval between ticks to make the appliance scheduling, this will be explained in the followings subsections. The house entity represents a consumer in the main simulation.

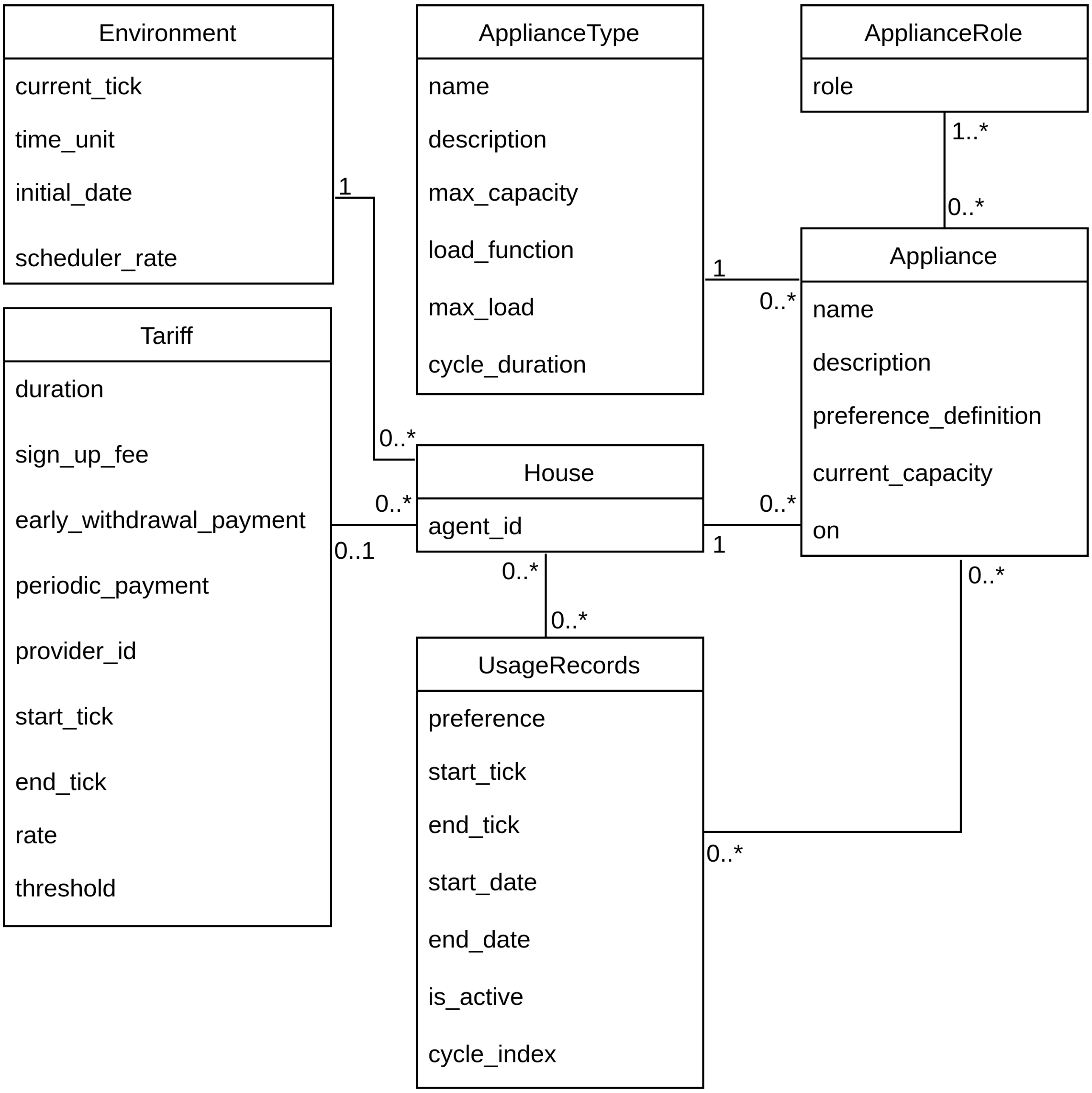

Figure 4.3: Database model

This entity has a single agent id column. This column represents the consumer agent id on APM platform. With this, it is possible to map between a house in this platform and a consumer agent on APM platform. To get a consumption curve a house has a set of appliances.

Regarding the appliances, the appliance role entity represents the different roles that an appliance can assume. The roles are consumer, producer and storage. Pointing out that a given appliance can assume more than a role. The appliance type entity is an appliance template. Basically, an appliance type is an object and an appliance is the instance of that object. This entity contains the following fields: name, description, max capacity, load function, max load and cycle duration. The name field represents the appliance type name. The description fields represents the appliance type description. The max capacity field represents the maximum amount of energy that an appliance can store, this field was created thinking in batteries and electric cars. The load function field is a string containing the consumption curve of an appliance type, as the majority of appliances do not have a constant consumption. This string is a groovy script to be evaluated at run time, more details will be provided in subsection 4.4.1. The max load field represents, in kWh, the maximum consumption of a given appliance type and is used as a variable in the load function script. The cycle duration field represents, in minutes, the normal duration of execution of the given appliance type, although this field can be over-topped by appliances preferences. This field is also a variable in the load function script.

The appliance entity represents an instance of a given appliance type. It is possible to see this relationship in the real world, as, for instance, a given brand builds a microwave and thousands of clients buy it. This relationship in the database model tries to replicate this. This entity contains the following fields: name, description, preference definition and on. The name field represents the appliance name. The description field represents the appliance description. The preference definition field is a string that contains one or more expressions where each expression defines when should an appliance start to run, its execution time and its percentage of usage, more details will be provided in subsections 4.4.2 and 4.4.3. The current capacity field represents the amount of energy that a given appliance has stored, this field will be used only by appliances that can store energy (e.g. batteries). The on field represents if an appliance is currently switched on or not.

The usage records entity represents when should an appliance start and finish running. This entity contains the following fields: preference, start tick, end tick, start date, end date, is active and cycle index. The preference field is, as previously mentioned, a string containing an expression that defines when should an appliance start to run, its execution time and its percentage of usage, more details will be provided in subsection 4.4.2. This entity contains this field to indicate which preference from the appliance is being used. The start tick field indicates when should an appliance start his execution. The end tick field indicates when should an appliance end his execution. The start date field is the date corresponding to start tick, this is being saved for performance reasons to avoid unnecessary conversions. The end date field is the date corresponding to end tick, this is being saved for performance reasons to avoid unnecessary conversions. The is active field represents if an appliance is active or not, this is also being saved for performance reasons and will be explained in subsection 4.4.3.

The tariff entity represents the active tariff of each house. This entity contains the following fields: duration, sign up fee, early withdrawal payment, periodic payment, provider id, start tick, end tick, rate and threshold. The duration field represents, in weeks, the extensions of the contract. The sign-up fee field represents the cost of signing the contract. The early withdrawal payment field represents the cost of leaving the contract before it ends. The periodic payment field represents a fixed cost. The provider id field represents the id of the provider which provides the tariff. The start tick field represents the initial tick of the contract. The end tick field represents the end tick of the contract. The rate field represents the cost per kWh of energy. The threshold field represents, in kWh, the maximum amount of power that this contract allows the consumer to spend. This entity represents the model of a tariff that we used in this work.

4.4.1 Load Function Evaluation

An appliance does not have a constant consumption whereby having a constant field representing its load would not be a correct representation. To get a better representation, we decided to express an appliance load as a function. In equation 4.4, it is possible to see the load function formalization.

$$f(t, mL, mC, uL, cD, cT, cN) = \mathbb{R} \tag{4.4}$$

The load function field of an appliance type is a string representing a groovy script[9]. In this script, the user has some variables that can use when defining the function. These variables are:

- t → tick: current tick of simulation
- mL → maxLoad: maximum amount of energy an appliance needs
- mC → maxCapacity: maximum amount of energy an appliance can store
- uL → usageLevel: percentage of usage of a given appliance

An appliance execution can be based in cycles. For example, a fridge execution can be represented by cycles of a wave function. To simulate these behaviours, it is also possible to use three more variables related to cycles:

- cD → cycleDuration: duration, in tick, of the cycle
- cT → cycleTick: tick of the cycle
- cN → cycleNumber: number of cycle runs

In run time, the script will be evaluated using a GroovyShell object from our Java code after the binding of all the variables referred previously. In the service front-end it is possible to see a graphic of an appliance type function. The graphic has as the x-axis as ticks and as the y-axis as load. In Fig. 4.4, it is possible to see a fridge consumption, with a load function:

$$\frac{cycleTick}{cycleDuration} * maxLoad \tag{4.5}$$

The consumption of a TV can be represented as a step function. To represent a step function in the Groovy script, we can use if statements. In Fig. 4.5, it is possible to see a tv consumption with a load function as:

$$return(tick < 13 ? maxLoad : maxLoad * 0.2) \tag{4.6}$$

This approach allows a more correct representation of an appliance consumption. As demonstrated in Chapter 3, most of power simulation tools consider appliance load as a constant value.

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[9] More information available online at `http://groovy-lang.org/index.html`

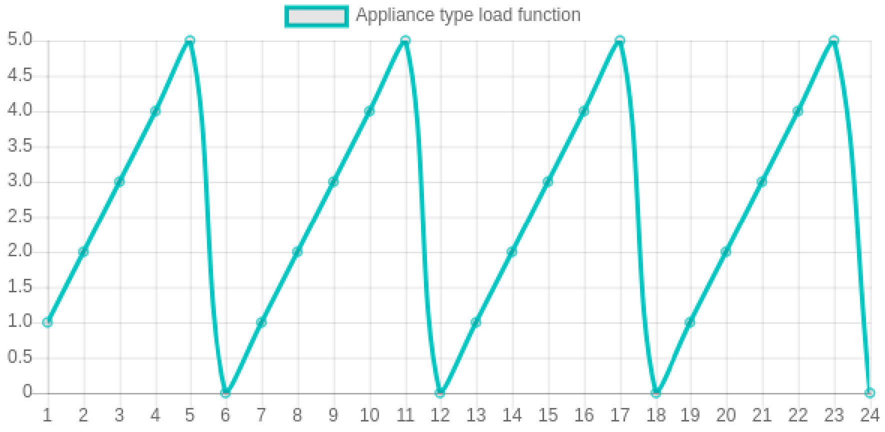


Figure 4.4: Graphic of a Fridge Load function

4.4.2 Scheduling Expressions

To define when should an appliance run we define an expression inspired in the ISO 8601 format [ISO, 2000]. This ISO format is used to write formatted date/times, duration and recurrence syntax in a cycle. In Equation 4.7, it is possible to see a simple formalisation of this expression. In Equation 4.8, it is possible to see an example of an expression.

$$<nofcycles>/<init\text{-}date>/<freq>/<time\text{-}interval>:<exec\text{-}time>:<usage> \tag{4.7}$$

$$R2/20190404T210000/P1D/200:50:100 \tag{4.8}$$

Equation 4.7 can be divided in three different sections, divided by a colon (:). The first section defines the preference itself and will be explained further ahead; the second section defines the execution time; and the third section defines the usage level of the appliance.

The preference section can be divided in four parts. The first part is used to define the number of times this expression will execute. The number after the letter ’R’, which stands for repetitions, indicates the number of repetitions. If there is no number between the ’R’ and the slash, we assume the expression defines an infinite number of repetitions. For example ’R2’, means that the appliance executes the expression twice. The second part defines the initial date for execution. The date needs to be defined in the format YYYYMMDD’T’HHmmss. With this date and frequency of execution (explained below), it is possible to obtain the number of executions and compare to the number in the first part. The third part defines the frequency. This section expects a ’P’, a number and a letter. The ’P’ stands for periodicity. The number is used to denote the frequency multiplier. The letter is used to denote time unit frequency between repetitions. Currently, our code supports four different time units frequencies: hourly, represented by ’H’ or ’h’; daily, represented by ’D’

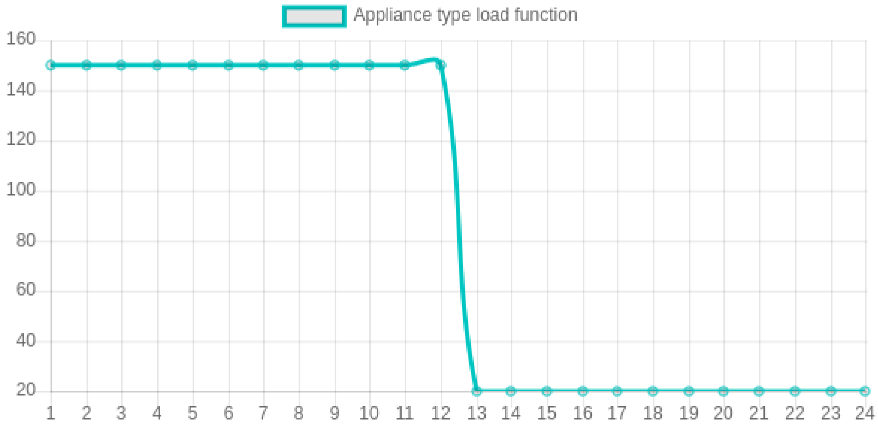


Figure 4.5: Graphic of a TV Load function

or 'd'; monthly, represented by 'M' or 'm'; and yearly, represented by 'Y' or 'y'. When merging the number and letter it is possible to obtain the time between cycles. For instance, 'P2D', means that the expression is repeated every two days. Finally, the fourth part defines a time interval in minutes that an appliance has to execute all the cycles specified in the first part. This means that this interval cannot be greater than the frequency defined in the third part.

$$R2/20190404T210000/P1D/200 \tag{4.9}$$

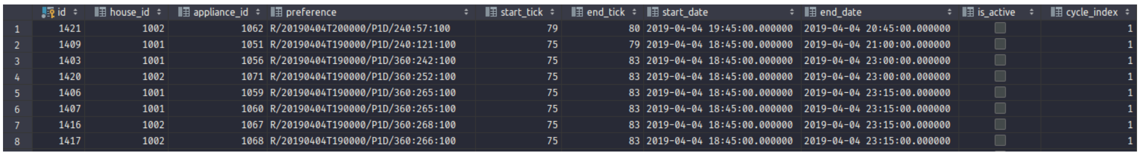
For example, for preference defined in Equation 4.9 means that this appliance will execute two days at 21:00 starting on 2019/04/04 in a space of 200 minutes.

$$R2/20190404T210000/P1D/200:50:100 \tag{4.10}$$

Merging, with the other two sections we get the complete definition of a preference. For example, an appliance with the preference stated in Equation 4.10 will execute two days at 21:00 starting on 2019/04/04 for 50 minutes in a space of 200 minutes at 100% of maximum load.

4.4.3 Appliances Scheduling

In the household simulation, we make a schedule of when all appliances should run. The time between every scheduling operation is defined in the scheduler rate variable of the environment entity. This variable is defined in ticks. A scheduler rate of 96, means that every 96 ticks our platform creates new appliances usages records. With the time unit variable also from the environment entity, we can get the conversion to minutes. A time unit (min) of 60 and a scheduler rate (ticks) of 24, means that the scheduling operation is executed every day. Every day, a schedule is created of which appliances should be running. Every appliance has a list of preferences ordered from the highest to the least priority. With this order it is possible to choose one when two or more preferences want to execute at the same time. With this approach, at each tick of simulation, the environment entity increments by one the current tick. Then this entity checks if: `currentTick % schedulerRate == 0` If it is equal to zero the house service is called to schedule otherwise is called to process the tick. When the process tick function is called, each appliance checks in the database if any usage record with his id and a start tick equal to the current tick exists. If there is, he starts executing. An example of usage records can be found in figure 4.6.



	id	house_id	appliance_id	preference	start_tick	end_tick	start_date	end_date	is_active	cycle_index
1	1421	1002	1062	R/20190404T200000/P1D/240:57:100	79	80	2019-04-04 19:45:00.000000	2019-04-04 20:45:00.000000	☐	1
2	1409	1001	1051	R/20190404T190000/P1D/240:121:100	75	79	2019-04-04 18:45:00.000000	2019-04-04 21:00:00.000000	☐	1
3	1403	1001	1056	R/20190404T190000/P1D/360:242:100	75	83	2019-04-04 18:45:00.000000	2019-04-04 23:00:00.000000	☐	1
4	1420	1002	1071	R/20190404T190000/P1D/360:252:100	75	83	2019-04-04 18:45:00.000000	2019-04-04 23:00:00.000000	☐	1
5	1406	1001	1059	R/20190404T190000/P1D/360:265:100	75	83	2019-04-04 18:45:00.000000	2019-04-04 23:15:00.000000	☐	1
6	1407	1001	1060	R/20190404T190000/P1D/360:265:100	75	83	2019-04-04 18:45:00.000000	2019-04-04 23:15:00.000000	☐	1
7	1416	1002	1067	R/20190404T190000/P1D/360:268:100	75	83	2019-04-04 18:45:00.000000	2019-04-04 23:15:00.000000	☐	1
8	1417	1002	1068	R/20190404T190000/P1D/360:266:100	75	83	2019-04-04 18:45:00.000000	2019-04-04 23:15:00.000000	☐	1

Figure 4.6: Usage Records Example

When the schedule function is called, each appliance plans for the next scheduler rate ticks when should run. Plans, by getting all his preferences. For each preference, using the date present in the preference definition as a template generates dates between the last usage or since the beginning of the simulation. After generating all the dates, tries to find if there is any between the current simulation date and the next tick date. Remembering that the difference between these dates depends on the time unit environment variable. If it finds a date between, this means that the preference is valid. Before creating a usage record, a random is done taking into consideration that the appliance has an interval to execute and a shorter execution time. If the remaining time of the interval is equal to the execution time, a usage record is immediately created. If not, the usage record is created depending on the random. This approach allows a flexible and efficient way to schedule all the appliances in the system.

4.4.4 Houses Generation

Our simulation needed a considerable amount of houses. Therefore, we implemented a house generator. To work, this generator needs the existence of appliance types to be able to create appliances. We divided the houses into three different groups: high consumption, average consumption and low consumption. The difference between them is the number of appliances in each house. We did this division trying to replicate houses from the upper class to the lower class of income. This algorithm starts by asking the number of houses in each group. Then goes for each group and creates the corresponding number of houses. For each house, it creates appliances from the existing appliance types. Appliances types used for now are tvs, coffee makers, gaming pcs, laptops, microwaves, fridges, clothes dryers, dishwashers, air conditioners and light bulbs. For each appliance type, we defined a set of preferences and we randomly generate the initial hour and the duration of execution. For example, for one preference for a laptop, we randomly select the initial hour between 18 pm and 22 pm and the duration between 30 to 130 minutes. It's not the most complicated system but it's not totally dummy either. However, because of this approach house load graphs are not similar to reality.

The number of appliances in each house depends on which group it belongs to. For the high consumption houses, it creates between 22 and 53 appliances. For the medium consumption houses, it creates between 18 and 30 appliances. And for the low consumption houses, it creates between 7 and 17 appliances. After the creation of all the appliances of a given house, a POST request is sent to APM platform. This request is sent in order to create an agent using the consumer process with a house id as a starting variable (to be explained further ahead). The response of the request returns the id of the created agent, which is saved by the house. The intent of this last step is to map a consumer from APM platform to a house in this platform. This approach will facilitate when creating community providers for specific groups. We can easily create three different communities, high, medium and low consumption.

4.4.5 Tariff Choice

Consumers need the capability of comparing tariffs. We attempted to model a typical consumer, who always chooses what he believes is the least expensive tariff. They need this capacity to understand when to change tariff. A consumer goal is to minimize cost, which is calculated weekly. The idea behind this model is to determine the time horizon when a change of tariff starts to pay off. For now, future load estimation is based on the past load, and determining this temporal horizon becomes as simple as determining the intersection between the lines that represent the cost of each pair of tariffs. Equation 4.11 defines the weekly cost calculation (where l_w represents the weekly consumer load and p_w the tariff price per energy unit):

$$C_{weekly}(l_w, p_w) = l_w * p_w \tag{4.11}$$

So when comparing T1, the current tariff, with T2 we seek to find the number of weeks that it takes for T2 to be better than T1. Equation 4.12 captures that, where T represents time (number of weeks), $T1$ represents the current tariff, $T2$ the tariff being analyzed, l the predicted weekly load, w the withdrawal fee, and s the sign up fee:

$$T \times (l \times p_{T1}) = T \times (l \times p_{T2}) + w_{T1} + s_{T2} \tag{4.12}$$

Solving Equation 4.12 with respect to T, we obtain Equation 4.13:

$$T = \frac{[l * p_{T2}] - [l * p_{T1}]}{-(w_{T1} + s_{T2})} \tag{4.13}$$

T represents the number of weeks necessary for the change of tariff to start compensating. In this work, three weeks was the threshold used. That is, if it takes three weeks or less to start compensating, the consumer will choose the new tariff and will proceed to the tariff change.

4.5 Agent Process Modelling Service

4.5.1 APM elements

The APM service is the one responsible for the agents execution (through creating and running processes instances). The idea is to model the entities we have been discussing: community providers, regular providers and customers in terms of their behaviour processes. To do that, we can use the APM service to design and store the processes that can programmatically be used to generate agent instances. The behaviours are then, represented as the orchestration of running and calling the agent capabilities (microservices) at the correct time.

4.5.2 BPMN elements

Beyond the whole set of BPMN elements and their specification (see Figure 4.7), there are some elements in which we are most interested in, also because they appear frequently in our processes.

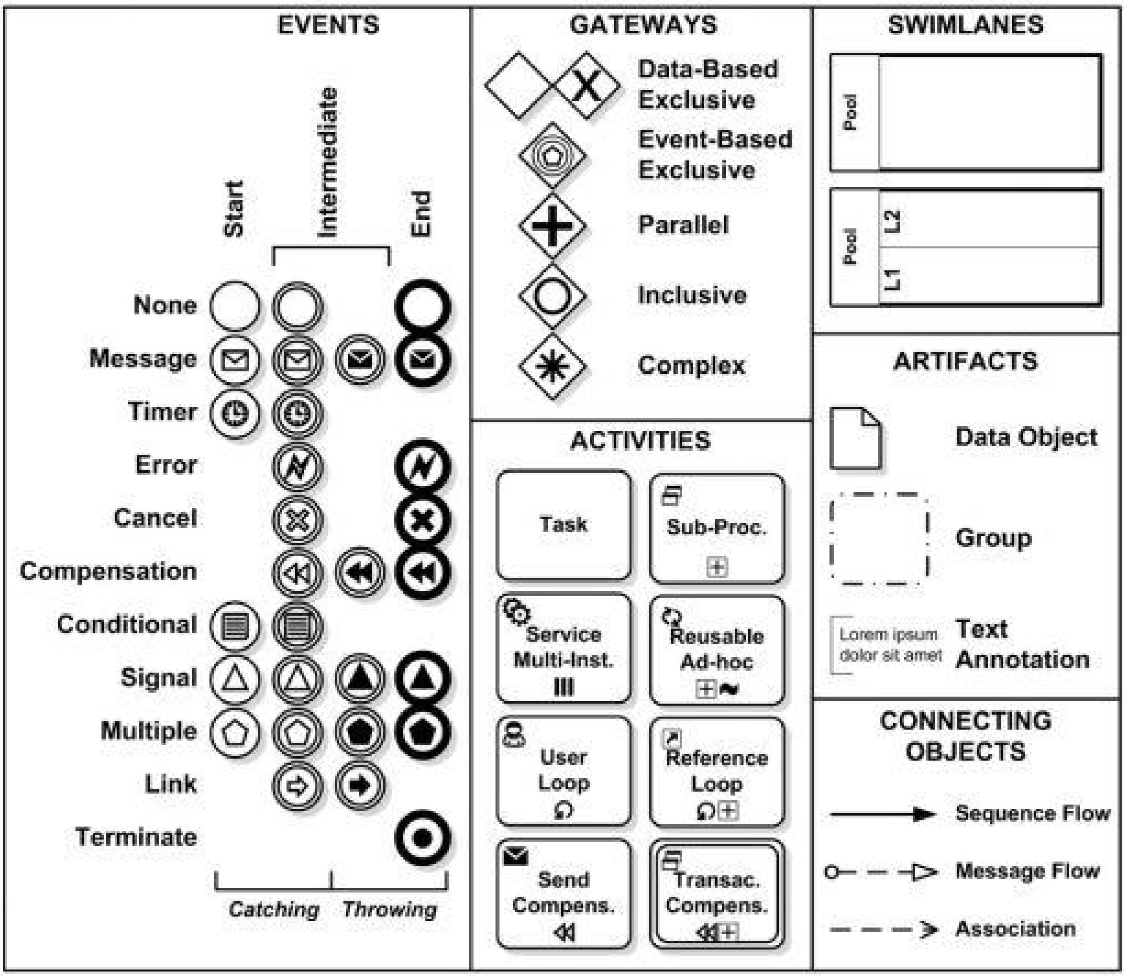


Figure 4.7: A subset of common BPMN elements

Starting with the event elements, we used five (Fig. 4.8). The start event that marks the beginning of a process. The end event that marks the end of a process. The intermediate catch message event which blocks the process waiting for new messages. The intermediate throw message event which sends a message. And the intermediate timer event used to block a process for a certain time.

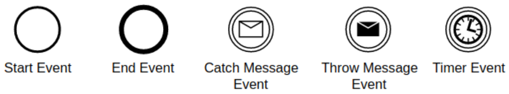


Figure 4.8: Frequently used events

From the gateway elements, we used three (Figure 4.9). The exclusive gateway that breaks the flow of a process, based on a condition, into one of the two or more mutually exclusive paths. The parallel gateway that is the opposite of the exclusive. It is used to represent two or more concurrent tasks. The event-based gateway that is similar to the exclusive. Both follow one flow. However, this gateway follows the flow from a given evaluated event (catch message, throw message, ...) not from which condition has been met.

Figure 4.9: Frequently used gateways

From the activities elements, we used two (Fig. 4.10). The script activity which executes a previously defined script. In our case, we use Groovy as a scripting language. This element was used to update process variables. Also used the service activity which can perform a call to a web service and send a message to other agents.

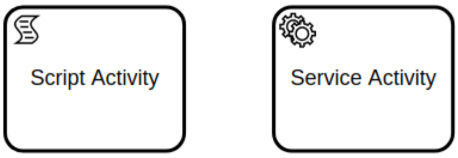


Figure 4.10: Frequently used activities

Besides all these elements, the sequence flow was used to connect all the process objects. Sequence flow can have conditions.

4.5.3 Agent Models

In order to run our simulation, we needed three different agents. For that, we needed to define three different processes. A consumer that subscribes to a tariff and tries to minimize cost. A provider which provides a tariff and tries to maximize profit and global market share. And a community provider, being a provider and consumer at the same time, that tries to maximize profit and target market share.

4.5.3.1 Consumer

A consumer is an entity that subscribes a tariff and pays a value in return. In Fig. 4.11, is possible to see the modelled process for our consumer.

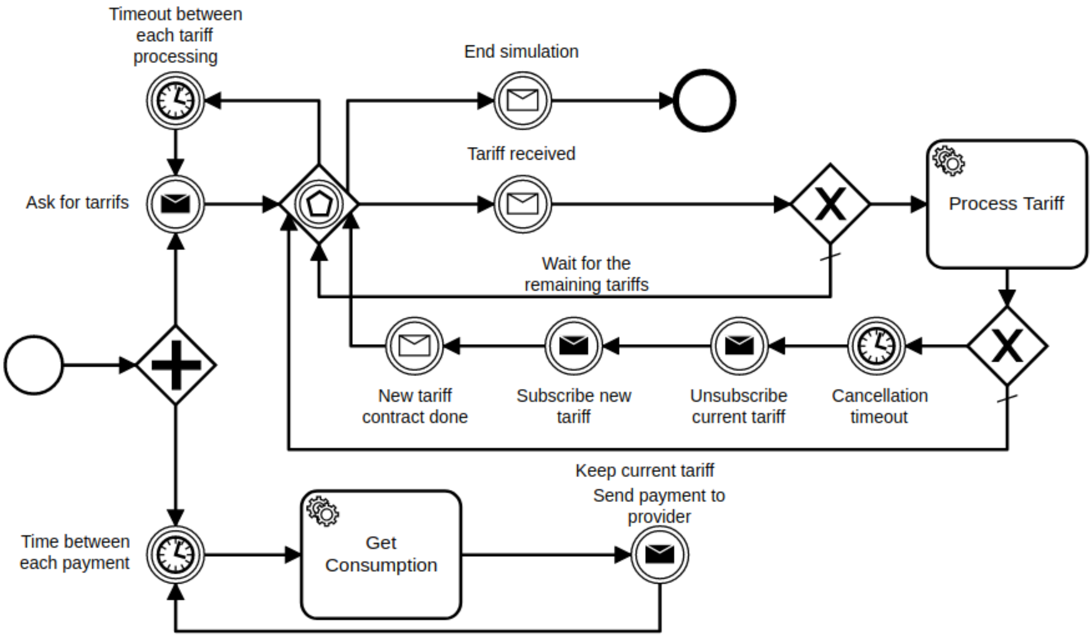


Figure 4.11: Consumer process

This process starts with a parallel gateway. Meaning this a creation of two sub-processes. One for tariffs processing and the other for tariff payment.

Starting by tariff update sub process, a consumer sends a message to all available providers to send their tariffs. After sending this message, it stays in the event loop gateway. Three events may occur. Receive an end simulation message, after this message the agent stops executing and dies. Receive a message from a provider with his tariff, in this case, the agent updates internal variables and checks if all tariffs have arrived. The verification is done by comparing the current tariffs with the number of providers to whom the message was sent. If all tariffs aren't received inside a time frame, the timer event will be triggered. This event will send the ask for tariffs message again and returns to the event loop, repeating the process. After receiving all the tariffs, the process goes through the exclusive gateway. Then calls a web service to process all received tariffs. This web service is an endpoint available in the household module. This endpoint will execute the flow explained in Subsection 4.4.5. If the decision is to keep the current tariff the process returns to the event loop and repeats all over again. If a better tariff is discovered, a cancellation timeout starts executing to simulate all the delays involved in cancellation processes. After the timeout, an unsubscribe message is sent to the provider holding the current tariff and fees are collected. After unsubscribing, a subscribe tariff is sent to the provider holding the new tariff. Afterwards, a contract done message is sent by the provider and the process returns to the event loop starting the sub process again.

The tariff payment sub process is a simpler process. Has a timer event to simulate tariff periodicity payment. At each timer event, the process sends a request to the household module. This request will return the current consumer consumption. With the consumption, tariff cost is calculated and sent to the provider. Returning, afterwards to the timer event. The payment process is started by the consumer instead of the provider for the sake of simplification in the implementation. Also, tariffs contracts are automatically renewed. After the first renovation, the loyalty period ceases to have an effect. Being the consumer free to leave the tariff without having to pay the early withdrawal fee.

4.5.3.2 Provider

A provider is an entity that buys electric power from the wholesale market and sells in the retail market. To sell power he provides a tariff. In Fig. 4.12, is possible to see the modelled process for our provider.

This process starts with a request to the tariff module. This request is necessary for the provider to obtain his tariff. Then the process arrives to an event loop. Six different events can occur:

- Receive a payment message: this message contains the consumption of the consumer and tariff cost. With this, the provider updates the profit and clients average load variables and returns to the event loop

- Timer event: from fixed amounts of time, the provider updates his tariff. In order to update, a request is sent to the tariff model. The update flow is explained in Subsection 4.3.1. After receiving the new tariff and updating internal process variables, returns to the event loop

- Receive end simulation message: after this message, the agent stops executing and dies

- Receive an ask tariff message: a message is received from a consumer asking for the provider tariff. The agent responds sending a message with his tariff and returns to the event loop

- Receive a subscribe message: a message is received from a consumer to subscribe to the tariff. The agent adds the client to his client's list and responds with an acknowledge message, returning to the event loop

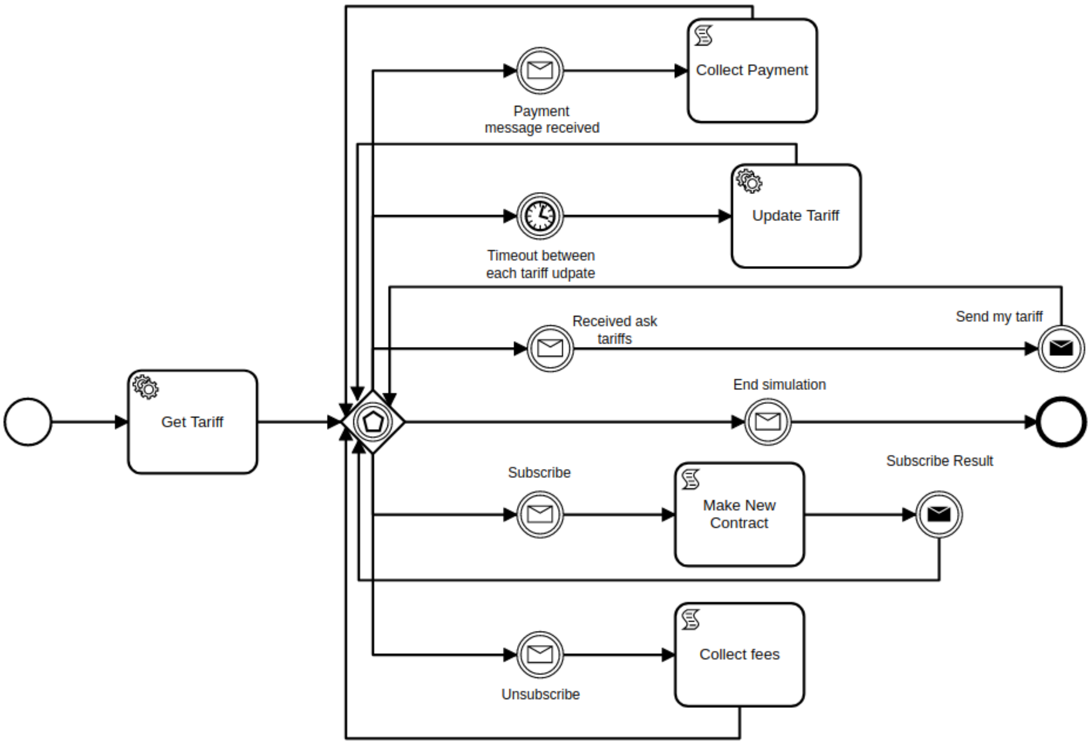


Figure 4.12: Provider process

- Receive an unsubscribe message: a message is received from a consumer to unsubscribe. The agent collects the fees related to an early withdrawal. Removes the clients from the client list and returns to the event loop

In our simulation, a provider only has a tariff. Real worlds providers have several tariffs in order to attract clients with different needs. We had to make this simplification to facilitate implementation. Although we can replicate the multiple tariffs by creating more providers.

4.5.3.3 Community Provider

A community provider is a new entity appearing in the electricity market. Like explained in background Chapter 2, a community provider is an intermediary between a consumer and a provider. For a provider, a community provider is a consumer. Also, a provider cannot distinguish between a consumer and a community provider. But a consumer can distinguish between a provider and a community provider.

The process modelled for the community provider agent is the same as the regular provider (Fig.4.12). Due to time limitations, it was not possible to implement the purchase of energy from providers. The differences between the regular and community provider are the decision models. The tariff update is different (section 4.3.1.2), a distinct service is called. Also, this process knows their target clients and has variables holding that values.

4.6 Microservices Integration

In order to run our simulation, microservices needed to communicate between them. This communication is done through a REST API. The three services expose a public REST API. Next paragraphs contain a brief explanation about services integration. We can divide services integration in two, APM platform with the household module and APM platform with the tariff module.

Fig. 4.13 shows integration's made between the APM platform and the household module. The figure is built to demonstrate the flow of the simulation. Before starting the simulation, the household service creates for each house a consumer agent in APM platform. Then, after starting the simulation, each consumer agent has two parallel flows. The payment and the update tariff flow, both explained in the previous section.

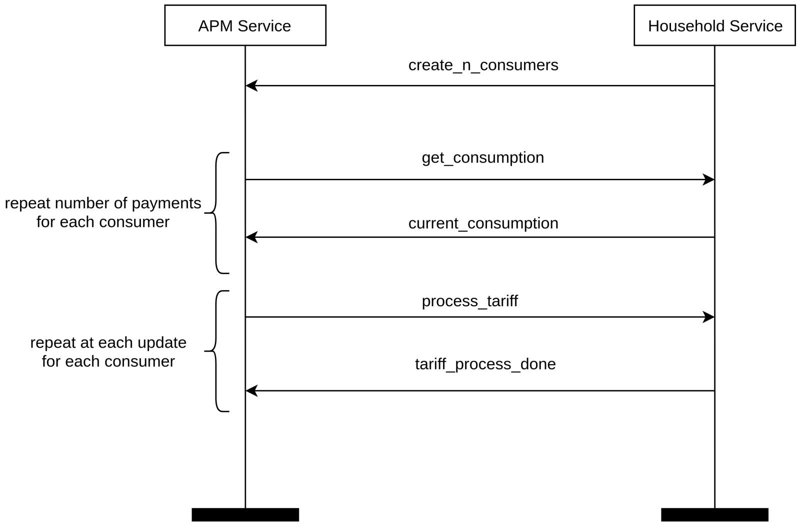


Figure 4.13: APM household integration

For the payment flow, the agent sends a request to get his current consumption. Receiving from the household service a number containing the current consumption. For the update tariff flow, the agents sends a request with all available tariffs. Receiving from the household service an object, representing the updated tariff. Which can be the same or another one.

Fig. 4.14 show integration's made between the APM platform and the tariff module. The figure is built to demonstrate the flow of the simulation. Before starting the simulation, the tariff service creates a given number of providers depending on the simulation scenario. Then, after starting the simulation, each provider calls the tariff module to get his tariff. The module responds with an object containing a tariff, following the model explained in subsection 4.2. Then, at each update, a provider will send an update tariff request. This request contains metrics variables and the current tariff. Tariff model will apply the logic explained in subsection 4.3.1 and return the updated tariff.

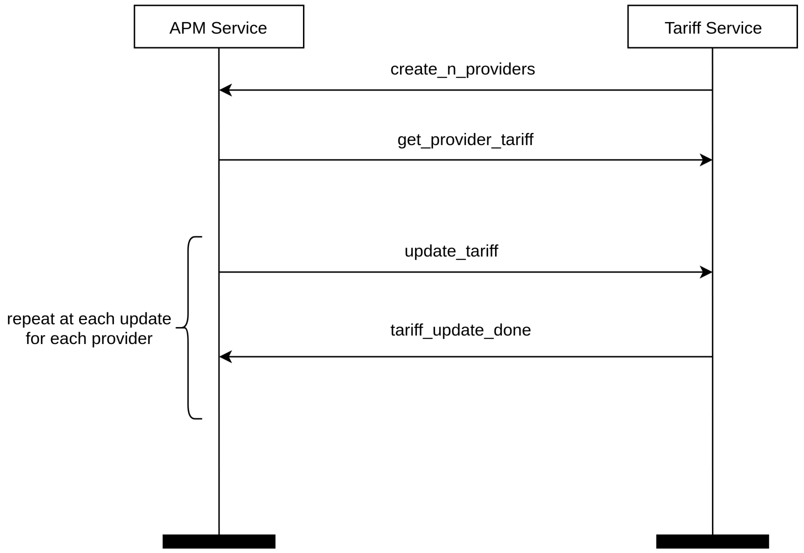


Figure 4.14: APM tariff integration

Chapter 5

Experimental Evaluation

This chapter contains the results of the simulations carried out. On Section 5.1 exposes the experimental design and runs configurations used. On Section 5.2 explains the metrics used to evaluate the different simulations scenarios. On Section 5.3 shows the results obtained. And on Section 5.4 presents a results discussion and analysis.

5.1 Experimental Design

To understand if a community provider can provide better tariffs then a regular provider we decide to run simulations on two different scenarios. A first scenario with the regular retail energy market. And a second scenario with community providers to replicate virtual markets inside the retail market. A multi-agent system is used to represent the retail energy market environment which has several different entities. Three different agents are modelled. Consumer, provider and a community provider. Time is modelled as ticks. In our simulations, a tick is equivalent to 60 minutes. The duration of both simulations is 2016 ticks, corresponding to 12 weeks of simulation. Updates and changes in tariffs are weekly, meaning that a provider will update tariffs twelve times. After running the two simulation scenarios, metrics can be compared and results exported.

The creation of initial provider tariffs (to be provided in the next sub-section) followed the logic that the price per kWh decreases as the amount of energy used increases [Bonbright et al., 1961]. Oppositely, fees increased with the increase in energy used.

To test our problem two different scenarios were thought. On the following table is possible to observe the run configurations used in both experiments.

Experiment	Ticks	Consumers	Providers	Communities Providers
1	2016 (12 weeks)	25	5	0
2	2016 (12 weeks)	25	5	2

In both scenarios, 25 consumers were used. The consumer population is divided into low, medium and high consumption like explained in Chapter 4. From the 25, 10 are low consumption, 10 are medium consumption and 5 are high consumption. This number of consumers were chosen due to limitations of the hardware used to run the simulations. Also, in both scenarios, 5 providers were used. This number of providers was decided to offer consumers a variety of tariffs at different levels of consumption. For last, in the first scenario do not exist community providers and in the second scenario, there are 2 community providers. These community providers have CT1 and CT2 as their tariffs and as target population the low and medium groups, respectively.

Tariff	Duration	Withdraw Fee	Periodic Payment	Sign-up Fee	Rate	Threshold
T1	10	150	10	50	0.24	700
T2	10	200	15	80	0.22	750
T3	10	300	17	100	0.2	1100
T4	10	400	20	150	0.18	1250
T5	10	500	25	200	0.16	1600
CT1	10	175	12	75	0.23	750
CT2	10	350	16	125	0.21	1200

In the table above it is possible to observe the tariffs used in both simulation scenarios. T_n, means the tariff from provider number n. CT_n, means the tariff from the community provider number m. On the first simulation scenario T1, T2, T3, T4 and T5 are used by the 5 providers. And on the second simulation scenario T1, T2, T3, T4, T5, CT1 and CT2 used by the 5 providers and the 2 community providers.

Tariffs T1 and T2 are more appropriate for low consumption consumers. Tariffs T3 and T4 are more appropriate for medium consumption consumers. And tariff T5 is more appropriate for high consumption consumers. CT1 has as target group the low consumption consumers and CT2 has as target group the medium consumption consumers.

5.2 Metrics

We created two groups of metrics to compare the simulations. One group for consumers and another for providers and community providers.

The metrics for consumers are:

- Tariff Cost: representing the weekly average tariff cost per consumption group throughout the simulation. This metric will help in understand consumers choices in tariff changes

The metrics for providers and community providers are:

- Profit: representing the amount of profit that a provider gets, weekly, from selling energy. Fees are also included in this metric.
- Market Share/Target Market Share: representing the percentage of clients in the market or in community provider case the percentage of clients inside the target group of consumers.
- New clients: this metric represents the number of clients who subscribed to a new tariff in each week.
- Clients leaving the tariff: this metric represents the number of clients who unsubscribed from a tariff in each week.

These metrics will be used to try to understand the impact caused by the communities providers and also to compare both simulations. Charts containing the metrics will be shown when displaying the results.

5.3 Results

5.3.1 First Scenario

The first simulation scenario tried to imitate a regular retail market with consumers and providers. Charts containing provider metrics for all five different tariffs will be shown. Charts containing consumers metrics will also be shown. Finishing with a short text on the insights of the results. The data available in the charts is the average of three different runs.

5.3.1.1 Providers Results

In Fig.5.1, it is possible to observe the number of clients of all providers over the weeks of simulation. Analysing the chart of T1 and T2 tariffs (top left corner) the number of clients floated a lot. T2 started with a higher number of customers but then T1 gained some. Then, this trend was reversed. This can be explained by the tariff update carried out by the providers. With more clients, they try to slightly increase the rate to maximize profit while the other provider decreases the price of attracting new customers. A similar trend is possible to observe in the chart of T3 and T4 tariffs (top right corner). Analysing T5 chart (bottom) it is understood that it attracted the customers of greater consumption and managed to maintain them until the end of the simulation.

In Fig.5.2, it is possible to observe the number of changes along the weeks. In the first three weeks, there were no consumers switching tariffs. This can, probably, be explained because all customers chose a tariff at the beginning of simulation and then the providers began to update. With the weekly updates some tariffs have become more attractive to some consumers opting for the exchange. After these weeks almost always there were tariff changes. During the simulation there were 15 tariff changes. Of those 15: 7 were from consumers who traded once and 2 consumers who traded twice. Averaging 1,15 change of tariff per week. About unsubscribes: T1 had 2, T2 had 3, T3 had 4, T4 had 5 and T5 had 1.

5.3.1.2 Consumers Results

In Figure 5.2, it is possible to see consumer metrics charts. We decided to group charts by load consumption. In these metrics, we can see that both tariff cost and load do not alter much. Tariff cost does not alter much is due to the fact that the consumers change of tariff when is becoming more expensive. Thus avoiding an overall increase in the cost of the tariff. Load consumption does not alter much because of the random preferences we did explain before.

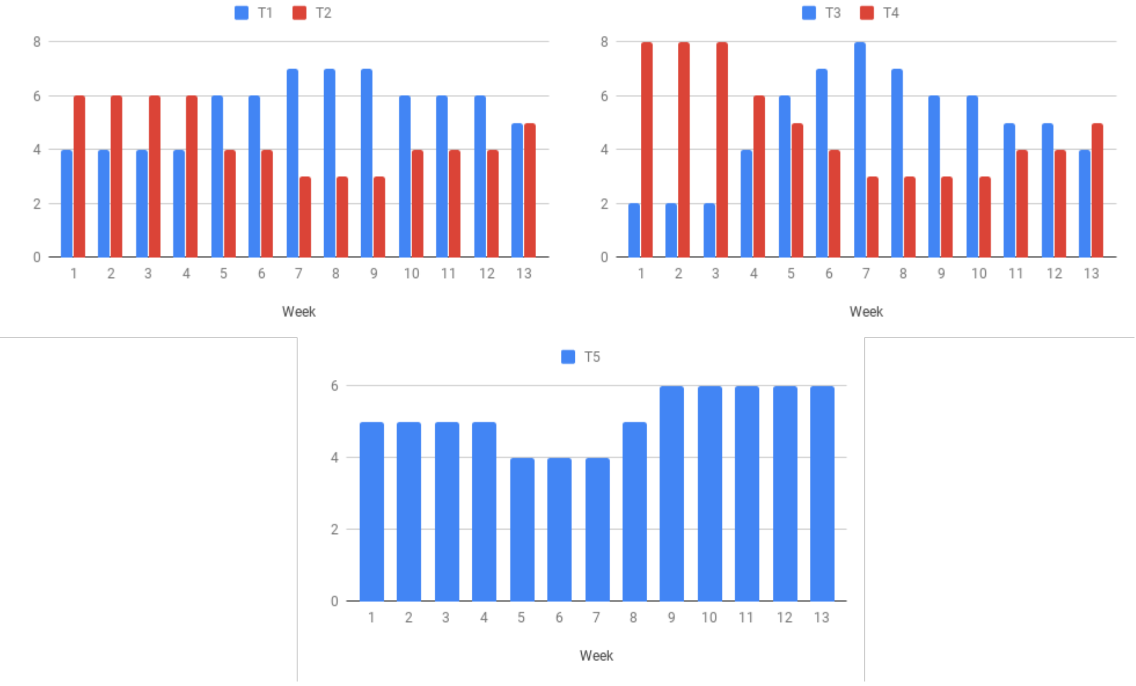


Figure 5.1: Experiment 1: Number of clients by provider

5.3.1.3 Results Remarks

The first insight of this simulation scenario was the market segmentation by consumption. Both for T1/T2 and T3/T4 clients where switching between them searching for cheaper rates depending on their consumption and the value of the fees. This created a flow in which customers first decided a tariff. The tariff with more customers slightly increased price. After a few weeks of increase, customers eventually switched to the other target tariff. This tariff was more attractive because of the few customers. Their updates have improved conditions from the point of view of consumers. This cycle of increase and exchange would, probably, continue to be repeated if the simulation were longer, creating a more unstable and less cohesive market. As T5 had no competing tariffs, it ended up having full control of the high consumption market, creating a monopoly. However, it followed the update logic explained before and did not abuse the fact that it did not have direct competitors. Customer base remained more or less constant throughout the simulation. We decided not to create a direct competitor of T5 to verify what happened. If T5 had competition a similar scenario to T1/T2 and T3/T4 had happened.

5.3.2 Second Scenario

The second simulation scenario tried to imitate a regular retail market with virtual markets. With consumers, providers and communities providers. Charts containing provider/community provider metrics for all seven different tariffs will be shown. Charts containing consumers metrics will also

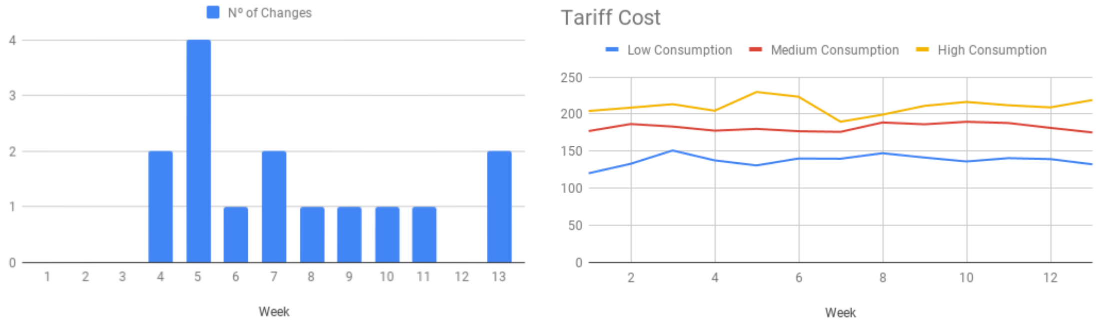


Figure 5.2: Experiment 1: Provider number of changes each week and consumer profit

be shown. Finishing with a short text on the insights of the results. The data available in the charts is the average of three different runs.

5.3.2.1 Providers Results

In this scenario, two communities providers were added. CT1 and CT2 correspond to the tariffs of these communities providers. Meaning this, a different logic when updating the tariff using knowledge about their target consumers. CT1 had as target community low consumption consumers and CT2 had as target community medium consumption consumers. T1, T3, T2, T4 and T5 remained regular providers. Starting conditions were equal to the previous scenario.

In Fig.5.3, it is possible to observe the number of clients of all providers over the weeks of simulation. Analysing the chart of T1, T2 and CT1 tariffs (top left corner) the number of clients floated a lot in the first eight weeks. However, only at eight weeks, CT1 began to gain clients to T1 and T2. In this scenario did not repeat the trend of the previous experience in which customers jumped tariffs. The same happened with the rates T3, T4 and CT2 (top right corner). Analysing T5 chart (bottom left corner) little has changed from previous experience. Looking at these charts it seems that the tariffs of the communities providers have managed to attract and insure their customers. From the chart in the bottom right corner, we realize that customers in the CT1 and CT2 tariffs are their target customers, both end up with 70% of their target market share.

In Fig.5.4, it is possible to observe the number of changes along the weeks. In the first three weeks, there were no consumers switching tariffs. This can, probably, be explained because all customers chose a tariff at the beginning of simulation and then the providers began to update. With the weekly updates some tariffs have become more attractive to some consumers opting for the exchange. However, in this scenario compared to the previous one there were less tariff changes. During the simulation there were 10 tariff changes. Of those 10: 6 were from consumers who traded once and 2 consumers who traded twice. Averaging 0,77 change of tariff per week. About unsubscribes: T1 had 2, T2 had 3, T3 had 2, T4 had 2, T5 had 1, CT1 had 0 and CT2 had 0. With this data, it is possible to infer that community providers succeeded in attracting

Figure 5.3: Experiment 2: Number of clients by provider

and maintaining their target customers. Nevertheless, it is not possible to guarantee that if the simulation had a duration of more than three months CT1 and CT2 per customers

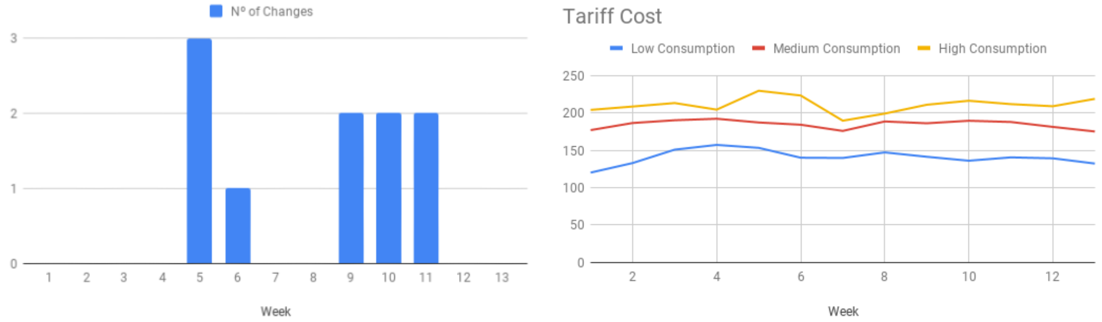


Figure 5.4: Experiment 2: Provider number of changes each week and consumer profit

5.3.2.2 Consumer Charts

In Fig.5.4, it is possible to see the consumers charts for the second simulation scenario. We decided to group consumers by load group. Comparing to the previous experience, there is not a big difference.

5.3.2.3 Results Remarks

This simulation scenario seems to point out that the communities providers succeeded in attracting and maintaining customers. This can be explained by the different logic in the tariff update. This logic has more knowledge about his target customers, as explained in Section 4.3.1. With the use of this knowledge, communities providers managed to keep customers. However, if the simulation lasted longer then customers could start getting out of the tariff. It is not possible to predict what would happen, it would require a longer simulation.

5.4 Experimental Results Analysis

The first simulation scenario, a regular retail market, where customers followed a flow present in decentralised markets. This flow was to subscribe a tariff, after some time a better option appears and they switched. That is, clients are always searching for better alternatives. Results for the first simulation scenario demonstrated a similar flow.

In the second simulation experiment, a retail market with community providers, the flow seemed to be different. This scenario started in a similar way to the first scenario, however as the weeks passed, clients began to migrate to the community provider tariff and stay there without changing. Nevertheless, if the simulation were longer, customers could start exchanging tariffs as they did with the tariffs of regular providers. A longer simulation must be performed to see if this behaviour will be maintained.

Without being sure that the community providers tariffs would keep their customers, it is possible to see that they have been able to attract their target customers. In the chart of the community provider target market share (Fig.5.3), it is possible to see that both of these entities ended the simulation with 70% of their target customers.

With these results, it is possible to conclude that the community provider managed to attract its target customers, yet we can not be sure if they will keep them.

Chapter 6

Conclusions and Future Work

This chapter summarises the contributions of this work through an overview of the major issues tackled by this thesis. Aiming for the discussion about whether our hypothesis were confirmed by our experimental findings or not we explain the results looking for future challenges and research fields that could be opened by this work.

6.1 Conclusions

The smart grid is a vast field of research with numerous new problems. We started by looking at the grids market. The smart grids market is changing from a centralized scenario to a decentralized scenario like explained before. This switch in market architecture gives more options to the consumer. Consumers have a larger portfolio of options. With more options, the market becomes more unstable. To providers, this means new strategies to sell electric energy. However, it becomes difficult to create appealing tariffs for all consumers, so tariffs turn out to be generics. On the topic of very generic tariffs comes the idea of community or virtual markets.

A community market is a group of consumers with a very similar consumption profile with a manager negotiating directly with providers. The manager, we call it community provider, has more bargaining power because it has the accumulated consumption of all members of the community. Therefore they can obtain a more attractive price by negotiating with the total consumption of the community compared to the sum of the prices obtained if each one of the consumers negotiates. Also, the community provider has more knowledge about members and is able to create suited tariffs. This can help in making customers want to stay at the current tariff they are.

To test if community providers can create more suited tariffs, two simulation scenarios were created. The first one to replicate the regular retail market and the second one to replicate a regular retail market with a communities markets. With these two scenarios, we can compare results.

After running the first simulation scenario we did see the normal flow in a decentralized market. Where, in this case, a customer subscribes to a tariff. The tariff starts becoming more expensive, then the customer looks for a better option e switches. Then this loop repeats. The beginning of the second simulation scenario was similar to the first one, however, with the passage of the week's consumers began to migrate to the tariff of the community provider. The difference was that customers ended up staying in the tariffs of the community providers. However, it is not possible to guarantee that this is due to the more suited tariffs or the short simulation period. Possibly with a longer duration of the simulation, consumers could begin to exit the community provider tariff going to a regular provider tariff. Simulations with a longer duration would be necessary. However, communities providers tariffs succeeded in attracting their target consumers.

The main contributions to knowledge on this work were the development of a MAS architecture of smart grid market to understand the impact of a virtual market inside it. And a module to simulate house consumption using a set of appliances loads. However, it has not been proven that communities composed of customers with similar profiles and a community provider aware of these profiles can provide more suited tariffs. A longer simulation would be necessary to prove this.

6.2 Limitations and Future Work

The simulation time was short to prove what this work has proposed. Therefore, new simulations with longer duration would be one of the directions for this work. Also, the tariff model was a limitation due to its simplicity. In the model, the calculation to obtain the value depend only on the consumption and the unit price. The unit price could change depending on the time or level of consumption. Depending on time multi-hour tariffs would be used. Depending on the level of consumption would enter on demand-side management. Also, new parameters like availability should be added. These improvements would bring the tariff model closer to reality. Besides, the community provider in its architecture buys from providers and sells to consumers. However, in this work, we only implement the sale to consumers. Therefore, implementing the purchase from regular providers would be a logical next step. Finally, the development of agents processes as well as their capabilities are also presented as future work. From agent capabilities, the most important decision models were the choice and update of the tariff. These models can be more worked up, even to use a different tariff model. A change in these models could completely change the experiences made since the simulations are very much attached to the agent's decision models.

Bibliography

[ISO, 2000] (2000). Date and time format - ISO 8601. Standard, International Organization for Standardization, Geneva, CH.

[Akter et al., 2016] Akter, M., Mahmud, M., and Oo, A. M. (2016). A hierarchical transactive energy management system for microgrids. In *Power and Energy Society General Meeting (PESGM), 2016, Boston, USA*, pages 1–5. IEEE.

[Asmus, 2010] Asmus, P. (2010). Microgrids, virtual power plants and our distributed energy future. *The Electricity Journal*, 23(10):72 – 82.

[Babic and Podobnik, 2014] Babic, J. and Podobnik, V. (2014). An analysis of power trading agent competition 2014. In Ceppi, S., David, E., Podobnik, V., Robu, V., Shehory, O., Stein, S., and Vetsikas, I. A., editors, *Agent-Mediated Electronic Commerce. Designing Trading Strategies and Mechanisms for Electronic Markets (AMEC), 2009, Budapest, Hungary,*, pages 1–15, Cham. Springer International Publishing.

[Bamberger et al., 2006] Bamberger, Y., Baptista, J., Belmans, R., Buchholz, B., Chebbo, M., Doblado, J., Efthymiou, V., Gallo, L., Handschin, E., Hatziargyriou, N., Jenkins, N., Kapetanovic, T., Keussen, U., Leffler, N., Moscoso-Osterkorn, M., Nabuurs, P., Østergaard, J., Sabelli, C., Elustondo, N., Smith, P., and Wasiluk-Hassa, M. (2006). *Vision and Strategy for Europe's Electricity Networks of the Future: European Technology PlatformSmartGrids*. Office for Official Publications of the European Communities.

[Bonbright et al., 1961] Bonbright, J. C., Danielsen, A. L., and Kamerschen, D. R. (1961). *Principles of public utility rates*. Columbia University Press New York.

[Borenstein, 2007] Borenstein, S. (2007). Electricity rate structures and the economics of solar pv: Could mandatory time-of-use rates undermine california's solar photovoltaic subsidies? *Study of Energy Markets*.

[Chassin et al., 2014] Chassin, D. P., Fuller, J. C., and Djilali, N. (2014). Gridlab-d: An agent-based simulation framework for smart grids. *Journal of Applied Mathematics*, 2014.

[Chinosi and Trombetta, 2012] Chinosi, M. and Trombetta, A. (2012). Bpmn: An introduction to the standard. *Computer Standards & Interfaces*, 34(1):124–134.

[Cory et al., 2009] Cory, K., Canavan, B., and Koenig, R. (2009). Power purchase agreement checklist for state and local governments. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States).

[David et al., 2010] David, E., Gerding, E., Sarne, D., and Shehory, O. (2010). *Agent-Mediated Electronic Commerce. Designing Trading Strategies and Mechanisms for Electronic Markets: AAMAS Workshop, AMEC 2009, Budapest, Hungary, May 12, 2009, and IJCAI Workshop, TADA 2009, Pasadena, CA, USA, July 13, 2009, Selected and Revised Papers*, volume 59. Springer.

[Fang et al., 2012] Fang, X., Misra, S., Xue, G., and Yang, D. (2012). Smart grid — the new and improved power grid: A survey. *IEEE Communications Surveys Tutorials*, 14(4):944–980.

[Fielding, 2000] Fielding, R. T. (2000). Rest: architectural styles and the design of network-based software architectures. Master's thesis, University of California.

[Gnansounou et al., 2007] Gnansounou, E., Pierre, S., Quintero, A., Dong, J., and Lahlou, A. (2007). A multi-agent approach for planning activities in decentralized electricity markets. *Knowledge-Based Systems*, 20(4):406 – 418.

[Grijalva and Tariq, 2011] Grijalva, S. and Tariq, M. U. (2011). Prosumer-based smart grid architecture enables a flat, sustainable electricity industry. In *Innovative Smart Grid Technologies (ISGT), 2011, Asia*, pages 1–6.

[Holland, 2006] Holland, J. H. (2006). Studying complex adaptive systems. *Journal of Systems Science and Complexity*, 19(1):1–8.

[Hu et al., 2018] Hu, J., Harmsen, R., Crijns-Graus, W., Worrell, E., and van den Broek, M. (2018). Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design. *Renewable and Sustainable Energy Reviews*, 81:2181 – 2195.

[Joskow, 2008] Joskow, P. (2008). Lessons learned from electricity market liberalization. *The Energy Journal*, 29:9–42.

[Ketter et al., 2013] Ketter, W., Collins, J., and Reddy, P. (2013). Power tac: A competitive economic simulation of the smart grid. *Energy Economics*, 39:262 – 270.

[Maier, 1998] Maier, M. W. (1998). Architecting principles for systems-of-systems. *Systems Engineering: The Journal of the International Council on Systems Engineering*, 1(4):267–284.

[Malik and Lehtonen, 2016] Malik, F. H. and Lehtonen, M. (2016). A review: Agents in smart grids. *Electric Power Systems Research*, 131:71 – 79.

[Mathavi et al., 2012] Mathavi, M. S., Vanitha, M. D., Jeyanthi, M. S., and Senthil, P. (2012). The smart home: renewable energy management system for smart grid based on ism band communications. *International Journal of Scientific& Engineering Research*, 3(3):1–8.

[Moret and Pinson, 2018] Moret, F. and Pinson, P. (2018). Energy collectives: a community and fairness based approach to future electricity markets. *IEEE Transactions on Power Systems*, pages 1–1.

[Morstyn and McCulloch, 2018] Morstyn, T. and McCulloch, M. (2018). Multi-class energy management for peer-to-peer energy trading driven by prosumer preferences. *IEEE Transactions on Power Systems*, pages 1–1.

[Moslehi and Kumar, 2010] Moslehi, K. and Kumar, R. (2010). A reliability perspective of the smart grid. *IEEE Transactions on Smart Grid*, 1(1):57–64.

[National Energy Technology Laboratory, 2007] National Energy Technology Laboratory (2007). A vision for the modern grid. Technical report, U.S. Department of Energy.

[Niazi and Hussain, 2011] Niazi, M. and Hussain, A. (2011). Agent-based computing from multi-agent systems to agent-based models: a visual survey. *Scientometrics*, 89(2):479.

[Onggo, 2012] Onggo, B. S. S. (2012). Bpmn pattern for agent-based simulation model representation. In *Proceedings of the 2012 Winter Simulation Conference (WSC), Berlin, Germany*, pages 1–10.

[Palensky and Dietrich, 2011] Palensky, P. and Dietrich, D. (2011). Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE Transactions on Industrial Informatics*, 7(3):381–388.

[Panajotovic et al., 2011] Panajotovic, B., Jankovic, M., and Odadzic, B. (2011). Ict and smart grid. In *10th International Conference on Telecommunication in Modern Satellite Cable and Broadcasting Services (TELSIKS), 2011, Niš, Serbia*, volume 1, pages 118–121.

[Rahimi and Ipakchi, 2010] Rahimi, F. and Ipakchi, A. (2010). Demand response as a market resource under the smart grid paradigm. *IEEE Transactions on Smart Grid*, 1(1):82–88.

[Ramchurn et al., 2011] Ramchurn, S. D., Vytelingum, P., Rogers, A., and Jennings, N. (2011). Agent-based control for decentralised demand side management in the smart grid. In *Proceedings of the 10th International Conference on Autonomous Agents and Multiagent Systems - Volume 1 (AAMAS), 2011, Richland, USA*, AAMAS '11, pages 5–12, Richland, SC. International Foundation for Autonomous Agents and Multiagent Systems.

[Ramchurn et al., 2012] Ramchurn, S. D., Vytelingum, P., Rogers, A., and Jennings, N. R. (2012). Putting the 'smarts' into the smart grid: A grand challenge for artificial intelligence. *Communications of the ACM*, 55(4):86–97.

[Richardson, 2014] Richardson, C. (2014). Pattern: Microservices architecture.(2014). *URL http://microservices. io/patterns/microservices. html.*

[Ringler et al., 2016] Ringler, P., Keles, D., and Fichtner, W. (2016). Agent-based modelling and simulation of smart electricity grids and markets – a literature review. *Renewable and Sustainable Energy Reviews*, 57:205 – 215.

[Rúbio et al., 2019] Rúbio, T. R. P. M., Lopes Cardoso, H., and Oliveira, E. (2019). Agent process modelling. In Demazeau, Y., Matson, E., Corchado, J. M., and De la Prieta, F., editors, *Advances in Practical Applications of Survivable Agents and Multi-Agent Systems: The PAAMS Collection*, pages 277–280, Cham. Springer International Publishing.

[Rúbio et al., 2017] Rúbio, T., Kokkinogenis, Z., Cardoso, H., Oliveira, E., and Rossetti, R. (2017). Resmas - a conceptual mas model for resource-based integrated markets. *Communications in Computer and Information Science*, 722:117–129.

[Scharff, 2015] Scharff, R. (2015). *Design of electricity markets for efficient balancing of wind power generation.* PhD thesis, KTH Royal Institute of Technology.

[Scharff and Amelin, 2016] Scharff, R. and Amelin, M. (2016). Trading behaviour on the continuous intraday market elbas. *Energy Policy*, 88:544–557.

[Schweppe et al., 1989] Schweppe, F. C., Daryanian, B., and Tabors, R. D. (1989). Algorithms for a spot price responding residential load controller. *IEEE Transactions on Power Systems*, 4(2):507–516.

[Shen and Norrie, 1999] Shen, W. and Norrie, D. H. (1999). Agent-based systems for intelligent manufacturing: a state-of-the-art survey. *Knowledge and information systems*, 1(2):129–156.

[Sousa et al., 2019] Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., and Sorin, E. (2019). Peer-to-peer and community-based markets: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 104:367 – 378.

[Stoft, 2002] Stoft, S. (2002). Power system economics. *Journal of Energy Literature*, 8:94–99.

[U.S Energy Information Administration, 2008] U.S Energy Information Administration, U. (2008). Factors affecting electricity prices.

[Vale et al., 2011] Vale, Z., Pinto, T., Praca, I., and Morais, H. (2011). Mascem: electricity markets simulation with strategic agents. *IEEE Intelligent Systems*, 26(2):9–17.

[Vandezande et al., 2009] Vandezande, L., Meeus, L., Belmans, R., Saguan, M., Glachant, J.-M., and Rious, V. (2009). Lacking balancing market harmonisation in europe: room for trader profits at the expense of economic efficiency? In *Proceedings of the 32nd International Association for Energy Economics International Conference (IAEE), June 21–24 2009, San Francisco, California, USA*, pages 17–pages.

[Verschae et al., 2016] Verschae, R., Kato, T., and Matsuyama, T. (2016). Energy management in prosumer communities: A coordinated approach. *Energies*, 9(7):562.

[Wang et al., 2013] Wang, H., Qian, Y., and Sharif, H. (2013). Multimedia communications over cognitive radio networks for smart grid applications. *IEEE Wireless Communications*, 20(4):125–132.

[Watkins, 1915] Watkins, G. P. (1915). A third factor in the variation of productivity: The load factor. *The American Economic Review*, 5(4):753–786.

[Yan et al., 2013] Yan, Y., Qian, Y., Sharif, H., and Tipper, D. (2013). A survey on smart grid communication infrastructures: Motivations, requirements and challenges. *IEEE Communications Surveys Tutorials*, 15(1):5–20.

[Yang, 2014] Yang, Y. (2014). Understanding household switching behavior in the retail electricity market. *Energy Policy*, 69:406 – 414.