FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Agent Strategies in Smart Energy Markets - PowerTAC

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DISSERTATION

Mestrado Integrado em Engenharia Informática e Computação

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Abstract

Current energy models and infrastructures need to be restructured in order to face the changes in energy consumption, production and management. The adoption of renewable power sources combined with the capability of a more reasonable and autonomous participation on the grid lead to this energy revolution. These changes demand improvements in the way participants act, not only related to the physical electricity grid, but mainly regarding related services, most notably energy markets. Since there is no real-life market to test new approaches for smart grid markets, simulations should be used. This work focuses on the PowerTAC simulation framework, a state-of-the-art platform in which competitors develop broker agents to enact market companies. In this context, the tariff composition problem plays a fundamental role since customers (both real and simulated) interact with the market by selecting a tariff. While creating and updating tariffs, the brokers should seek to remain competitive and still profitable. A broker's performance is given by its market share and profit on the market. Current competitors in the annual PowerTAC competition use a centralized approach, with focus on single features to compose tariffs. In this work an alternative approach to this problem is presented. We propose the creation of a Broker that is inherently a Multi-Agent System - a broker composed by different specialist agents that evaluate different features to compose the final tariff. To validate the performance of our approach, firstly we analysed the results of local experiments against competitors in previous editions of the competition and secondly, tried to qualify to the 2016 annual competition. The main takeaway form the results is that the wholesale market cannot be neglected

Resumo

Os atuais modelos e infraestruturas de energia precisam de ser reestruturados, de forma a enfrentar as alterações no consumo, produção e gestão de energia. Esta revolução energética foi causada pela adoção de fontes de energia renováveis em conjunto com a possibilidade de uma participaçao mais autónoma na rede de energia. Estas mudanças exigem melhorias na forma como os participantes se comportam, não apenas em relação à infraestrutura física, mas principalmente em relação aos mercados de energia.Por não existirem implementações reais de mercados de energia baseados em smart-grids, é necessário utilizar simulações. Esta dissertação foca-se na framework PowerTAC, uma plataforma de simulação em que os participantes desenvolvem agentes de software (brokers) que participam no mercado. Neste contecto, a composição de tarifas tem um papel fundamenta, já que os consumidores (tanto os reais como os simulados) interagem com o mercado através da escolha de tarifas. Durante os processos de criação e atualização das tarifas, os brokers devem tentar manter-se competitivos e ainda assim manter lucros positivos. A performance de um Broker é medida pelo market share alcançado, e pelos lucros obtidos. Os atuais participantes na competição anual PowerTAC aplicam uma abordagem centralizada, que cria tarifas focando-se apenas em alguns aspetos do mercado. Nesta dissertação, é apresentada uma alternativa. Propomos a criação de um broker baseado num Sistema Multi-Agente - um broker composto por vários agentes especialistas que avaliam diferentes aspetos de formas diferentes para compor a tarifa final. Para validar a performance da abordagem, inicialmente foram analisados os resultados de experiencias locais contra participantes em ediçoes anteriores da competição, e mais tarde através da participação nas rondas de qualificação para a edição de 2016 da competição. A principal conclusão retirada foi a de que o mercado de venda grossista não pode ser negligenciado.

Acknowledgements

I want to thank my supervisor, Henrique Lopes Cardoso, the second supervisor, Thiago Reis Pedroso Munhoz Rúbio, my family and my friends for the support they gave me during the development of this dissertation.

João Pedro Pinheiro

“What to do, when a ship carrying a hundred passengers suddenly capsizes and only one lifeboat?
When the lifeboat is full, those who hate life will try to load it with more people and sink the lot.
Those who love and respect life will take the ship’s axe and
sever the extra hands that cling to the sides of the boat.”

Pentti Linkola

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Chapter 1

Introduction

This chapter contains the introduction to the rest of the dissertation. There is an overview of the context in which the work is inserted, the questions that we tried to answer and the hypothesis that were placed and tested. There is also a brief review of the results obtained and of the steps taken throughout the course of the work.

1.1 Context

The way energy is being produced and used is changing. We're being faced with changes in the architecture of distribution systems, moving towards distributed models. The current models are becoming obsolete, since they are unable to answer emerging market needs and trends. Right now, it is not possible to monitor and control the grids, and the distribution is centralized, and unidirectional, being the energy production the job of big producers, that are, for instance in the case of renewable energy, exposed to changes in weather. In these cases, the supply does not follow the demand, but is influenced by some external factor, creating instability in the energy markets.

The increasing environmental awareness of people has led them to start using more efficient appliances that allow a more effective monitoring and controlling of their energy consumption. This allows consumers to tap into that information, unavailable until recently, and change their energy consumption habits, like changing the periods with the bigger energy loads to the times of the day when the energy tariff is lowest. The management of energy consumption and production is not only a customer worry, but a new trend characterized by the wide presence of distributed renewable energy generators in low voltage grids. This factor is imposing new challenges for main energy generation and distribution companies. In this new scenario companies are not able anymore to predict energy demand, given the limited visibility (units are unknown), the production volatility (weather uncertainty affects renewable generation) and the consumption flexibility (caused by smart grid and home automation technologies that can control and shift loads to improve customer efficiency).

All these characteristics increase the difficulty for generation companies and distribution utilities of keeping the electrical energy supply stable and with quality. In this sense, centralized control strategies used by supplier companies are not suitable to handle energy intermittent production regarding the large number of small size distributed renewable sources installed along grid elements. Therefore, it is necessary to create more flexible, decentralized and self-organizing control infrastructures and strategies capable of managing the grid.

1.1.1 Smart Grids and Energy Markets

A smart electricity grid is an upgraded active electricity network. It can intelligently integrate the actions of users that are connected, creating so-called 'prosumers' who are able to produce electricity as well as consume it. A smart grid ensures an efficient, sustainable electricity supply, with lower losses and greater reliability and security. Smart electrical meters, that will replace the existing ones, provide utilities with a secure, two-way flow of data and may form part of a smart grid. On the transmission side, the existing electricity grid will need to be expanded to accommodate remote renewable sources, since distribution grids are becoming increasingly bi-directional, changing the traditional principles based on which grids are planned and controlled. Increased energy efficiency – which mostly comes from residential buildings – and demand-side management of energy, are moderating consumption patterns, that require new advanced control procedures and greater harmonization between the unbundled transmission system operators, and distribution system operators. Smart grids are far more reliable, efficient and sustainable than regular energy grids. They provide access to a far greater amount of information than their predecessors, that can be used by the connected users to effectively predict energy consumption patterns, diminishing the risk for unexpected demand spikes, decreasing the likelihood of over, or under-production of energy, and all around making the *energy market* far more stable than it once was. This new type of energy market requires that new types of trading strategies are developed, that can accommodate all the variables present in the grid. The strategies must be able to provide the network with energetic balance, avoid spikes, and adjust the production to the demand, all while maintaining profits for everyone involved.

1.1.1.1 Services in the Smart-Grid

The functioning of the smart grid relies on the existence of a set of services that enable the connection between production and generation points. Services such as the distribution utility, energy markets and brokerage, information transmission and even the banking institutions play a part in the ecosystem. The distribution utility is the one that connects energy producers to the final consumers. Due to the nature of the grid, every connected point supports two-way flow of energy, since most participants have the ability to play both parts, that of the consumer and the producer.

Since the energy production and transmission are now unbundled, meaning it does not necessarily belong to the same entity, the Distribution Utility typically charges a fee for the transported energy. This is because the distribution network has to support maintenance costs, among other things. The transmission fee can be related to the amount of energy transmitted or not, depending on the operator.

The energy markets are a fundamental part of the Smart-Grid. Together with the *brokers*, they provide the interface where energy can be traded. Unrelated to the physical exchange of energy, the markets are the place where energy contracts are negotiated. There might be different types of markets, for different kinds of participants, such as a wholesale market and a retail market, but it is also possible, even if not practical, that everyone negotiates in the same market. Energy markets will typically be day-ahead markets, meaning the participants negotiate energy to be delivered or consumed in the day after. Energy brokers are responsible for the offer of energy contracts to individual consumers and producers. They can buy and sell energy in any market, and their final objective will generally be to maintain profit. While not being directly related to smart grid technology, the Banking Institutions provide a safe way to execute money transfers, facilitating payments, thus playing an important role in the system.

1.1.1.2 Customer Types

Another defining characteristic of Smart Grids is that unlike in traditional energy grids, participants are not divided between consumers and producers. The smart-grid technology allows for every consumer and producer to become a *prosumer*, meaning he can both buy and sell energy in the adequate markets. This means, for instance, domestic users, that have solar panels, can sell their excess energy in the market to whoever they choose, instead of being forced to trade with one buyer. Generally the energy is sold to a broker, who will then sell it to other consumers for a profit. Besides consuming and producing, customers can negotiate contracts for energy storage, to be delivered on the market, or used on a later date.

1.1.1.3 Energy Brokerage and Management

Since it is not practical to have the individual consumers trading directly with the generating companies, this interaction is usually mediated by a broker. There can be several different brokers participating in the markets, and each will execute its own trading strategy, depending on its own objectives. Generally, the broker buys energy from wholesale producers in one market, and sells it to consumers in a different market, oriented towards retail transactions; however, energy can also be bought in the retail market. As mentioned before, the trade in the wholesale market is done according to the rules of a day-ahead market, so the broker must predict how much energy will be required. At the same time, the broker composes energy contracts that are offered to the customers on the retail market.

Energy contracts, commonly referred to as *tariffs*, can have dynamic rates, can be oriented for consumption or production, be specialized in a certain type of production, like solar power,

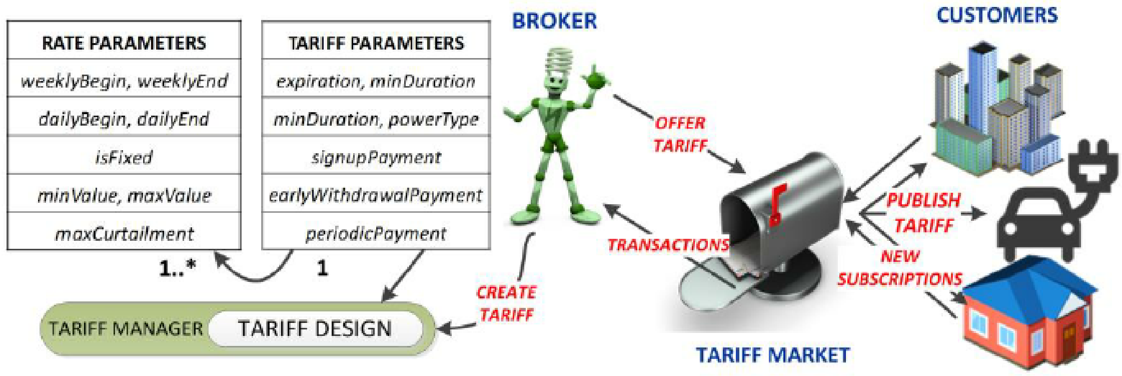

Figure 1.1: Tariff features and the Smart Grid market [Tal+13]

or consumption, like domestic or industrial. Minimum duration, withdrawal and sign up fees can also be specified. The specification of each tariff might be limited by the market in which it is offered, but there are no limitations imposed by the smart grid technology.

It is the Broker's function to guarantee its portfolio is balanced, meaning it does not sell more energy than it buys, as this will cause severe instability in the network, and endanger the system. The balancing of the portfolio should be considered in the broker strategies, since it is essential that the grid stays balanced.

1.1.2 The Tariff Problem

Since the marketplace is bound to become far more dynamic, the way tariffs and contracts are created will change to face the new conditions, which leads to the tariff composition problem. As seen, tariffs are the way managers can influence and control customer's behaviours. Thus, creating and updating tariffs to better fit broker's intentions and instant characteristics of the grid becomes a complex problem. In energy markets, tariffs determine the energy plan to be followed by customers.

A tariff defines energy quantities and prices to be applied in a given moment. Moreover, tariffs implement a regulation mechanism that specifies how much the customer will pay if it exceeds the current tariff limitations. Figure 1.1 shows the tariff features and how the agents could use tariffs to interact with the market. When a customer chooses a tariff, a contract is established and both parts should comply with the rules.

In fact, from the broker's point of view, tariffs should be competitive and profitable. This means that tariffs should attract customer's attention in such a manner that it intends to subscribe to that plan. On the other side, brokers should try to profit with tariff. When conditions change, operators should update the tariffs to prevent portfolio imbalances. A broker's portfolio is considered balanced when it does not sell more energy than it has available.

Being a real problem, customers present different behaviours regarding tariffs. Choosing a new tariff is not a reactive process, but rather a situation when all the relevant considerations imply breaking with the inertia of keeping the old energy plan. Customers usually try to seek tariffs that best fit their needs and meet their consumption/production profiles. Another point to consider is the effect different tariffs have on energy consumption. While the most obvious way to control consumption is to physically restrict it, it is also likely that customers' behaviour can be influenced by the tariffs they subscribe to. This could function in the same way price control does. In order to get the consumption to go down, an intuitive choice is to however, this interrelationship is much more intricate, touching also energy consumption habits, and must therefore be handled in a much more elaborate way.

In sum, analysing the tariff problem on the real world is a very difficult task since the smart grid architecture is still under implementation and deeper studies on consumption and production behaviours on smart grids are needed. For this purpose, simulation tools can be used.

1.1.3 Energy Market Simulation

Due to the lack of real world cases where hypothesis can be tested, the study of the future energy markets must be done relying on simulation tools. Simulation tools allow us to gain insight regarding a specific system's behaviour and to analyse the impact of changing parameters without the real-life consequences. As explained, energy market simulations are useful tools when designing new strategies for the smart grid market, where the study of the dynamic conditions is necessary. Simulated marketplaces present themselves as valuable prediction tools when played by the broker's point of view. Granted that the customer models being used are realistic, they can closely mimic the real environment where the broker will operate, allowing it to test different approaches and strategies, knowing the results would be very similar in a real life scenario. That however, is not yet the case, as most customer simulation models are very simplistic in nature. Developing new strategies for energy tariffs can lead to more efficient and profitable tariffs. Thus, the market provides regulators, with the information they need to ensure the market stays protected from abuse.

In fact, many simulation tools for energy market have been proposed in the last few years. Focusing on the two types of existing energy markets (Wholesale and Retail) and mathematical models that can represent participant behaviours well, each simulation framework has advantages and drawbacks. One common feature observed is that the inner distribution and autonomy required for the simulation objects is, in most of the cases, modelled as a Multi-Agent System (MAS). MAS are the natural evolution of the Object-Oriented Programming model in which the objects gain autonomic behaviours, knowledge and cognition. These objects are called agents, to be better explained on Section 2.4. The characteristics of a Multi-Agent System become especially useful in the simulation of real-life scenarios where different people with different objectives interact, such as traffic, customer trends, and more importantly, markets. The fact that this type of systems allow the creation of agents with different goals, strategies, and plans of action, makes them the more capable of properly simulating a real, dynamic, market. This makes Multi-Agent Systems a good approach for the simulation of the future energy markets. As we will see on the next sections, the problem with existing simulation tools is that although they can be considered MAS, the agents that interface the strategies developed with the system are usually monolithic, rigid structures that do not take advantage of using MAS technology.

1.1.4 Multi-Agent Systems

Multi-Agent systems are software systems composed of groups of independent agents, that can operate autonomously. The main difference from normal monolithic systems is the decentralization of the decision making process.

The characteristics of a Multi-Agent System become especially useful in the simulation of real-life scenarios where different people with different goals interact. The fact that this type of systems allow the creation of agents with different goals, strategies, and plans of action, makes them the more capable of properly simulating a real, dynamic market.

Multi-Agent Systems should also be able to make automatic decisions regarding their objectives. This, together with the autonomous operation, makes Multi-Agent Systems the most useful tool in the simulation of the Smart Grid based energy markets.

1.2 Problem

1.2.1 How to Create and Manage Efficient Tariffs

In this thesis, we will focus on the tariff composition problem. It means that when brokers create tariffs, they must always consider two sides. Firstly, they must take into account their own objectives, maximizing profits or market share, for instance. Secondly, they must remember that in order to achieve the desired results, the tariffs must also be coherent with the desires of the customers. A tariff that has exceedingly high prices would provide equally high profits, if not for the low customer interest it is likely to elicit. So the agent must find the point where its interests meet the customers' and produce a tariff based on that, so that a balance is found and success is achieved for both parties.

Since tariffs are the result of combining prices and quantities, the broker's task is to decide how to better adjust these two factors under its budget, gains and intended profit. Broker's actions could be directed towards incentivizing a specific type or groups of customers, or rather to focus on reducing the imbalances from consumption and production. Decomposing these many facets of the problem we discover a secondary, but not less important problem to tackle: how to combine broker's intentions with the information available? What are the features to be used on tariff composition and how a broker could manipulate the weight and importance of each feature in order to better adapt the tariff to system's state?

1.2.2 How can Software Agents be used to improve Tariff creation

As mentioned before, most of the simulation tools proposed so far, do not make full use of the capabilities of Multi-Agent Systems. On most of those simulation tools, the entities responsible for composing and proposing tariffs to customers are typically not distributed, always approaching the issue from the same perspective. It is possible however, to create a system that is composed by several different software agents, that will each approach the tariff creation from different perspectives, and with different objectives, Due to the potential for the development of more intricate strategies, it is possible that the use of software agents can improve the effectiveness of the Tariff Creation process.

1.2.3 How to Explore the Knowledge to Produce different Tariffs

According to what was said in the previous section, approaching the tariff creation problem from different angles can potentially provide better results. One approach that is likely to be useful is that of analysing previously gathered knowledge, about customers, markets and the environment in general. The way how this analysis should be performed, is one of the things that has been studied in this work. These are the questions we will seek to answer. We believe that the tariff problem addressed in this work is very important for future market strategies and that our contributions will show if our approach for this problem can enhance broker's decisions. To respond to all this we state our assumptions and hypothesis in the next section.

1.3 Hypothesis

Since there already exist various types of trading agents with different goals and strategies, and some specifically made to work in energy markets, it is possible that a strategy emerging from the combination of various trading and prediction techniques is the path to better results. We believe that within the information available on the energy markets, broker's can improve their tariffs. Moreover, we believe that MAS can bring advantages to aproach the tariff creation process. To seek the goals of this thesis, we create two hypothesis:

Hypothesis 1 (H1): *Considering agents as specialists on subdomains (such as weather, supply and demand forecasts) that have complementary insights for the tariff, they can coordinate to create a final tariff.*

The analysis and understanding of the way existing PowerTAC competitors work, and how their strategies relate to their successes and failures, can be a valuable source of information and can provide the direction for the development of even better strategies that produce superior results.

The application of strategies using an approach based on Multi Agent Systems can also be a way to increase effectiveness. Since the MAS simulations are the ones that more closely resemble a real market, MAS oriented strategies are likely to produce results surpassing those of conventional strategies, or of those designed without the characteristics of MAS in mind.

Hypothesis 2 (H2): *Representing a Broker as a Multi-Agent System, we can enhance the performance of the tariff on the market, not only for the broker (profitability) but also for the customers (attractiveness).*

1.4 Main Results

The outcomes from this research comprise an analysis on future energy markets and how multi-agent systems can be applied to that scenario. We can divide the results of this thesis in four main contributions:

- **Development of a MAS architecture -** The work related to the development of the broker has resulted in the development of a Multi-Agent System Architecture that is applicable to energy markets.

- **Development of new models for tariff Selection -** The part of the Multi-Agent System that is responsible for reaching a decision about the tariff management does so with the use of a decision system based on an evaluation of each tariff utility.

- **Proposal for a Predictive Tariff creation model -** A model for tariff creation based on the analysis of previous data with the use of data mining and prediction techniques was proposed but only partially implemented.

- **Broker improvement with this strategy -** One of the most important results was the improvement of energy brokers. Using the developed architecture, it is far more simple to develop a new broker, to test new strategies. Even if there is no immediate direct impact on the performance of the broker, the increase in potential for further development when compared with a traditional, monolithic approach, was a large improvement on the current state of automated energy brokers.

1.5 Methodology

In the near future where Smart Grids take place, it will be very necessary to predict how the interactions between participants in the market will occur, the type of strategies, that can be applied, and their possible consequences. Additionally it will be essential to know what kind of regulations will need to be in place in order to ensure that the future energy markets stay stable, safe, and free of exploitation. This work aims to improve the understanding of the inner workings of future energy markets, by studying how the existent simulations of these markets work, and proposing and testing ways to make them work better and more efficiently increasing the advantages to all participants. Our research methodology is described as follows:

- **Problem-oriented research**

  Since the inner-workings of markets cannot be put under one category of study, broadening the focus of the research makes sense. Focusing exclusively on specific approaches, such as Multi Agent Systems, can prove to have some significant shortcomings, so we focused on the problem, rather than on areas of study.

- **Literature review**

  Reviewing existing literature that is related to the area of the work, is always an important and useful tool. It allows one to build on the work of others, pursuing paths that are promissory, and avoiding those that are shown to have no value. The literature that was reviewed is related to Multi-Agent Systems, Smart-Grids and Artificial Intelligence

- **Competitor's comparison**

  Since there already exist trading agents built to compete in energy markets, it made sense to make an in-depth comparison between them, with their advantages and drawbacks.

- **Development of the Broker**

  After the research was done, and the relevant information gathered, the energy broker was built. This was done taking in consideration what was been learned until this point, in order to produce an agent as competent as possible.

  The broker is a software agent, capable of trading in energy markets, and adopting strategies in order to achieve a desired outcome.

- **Simulation results analysis**

  After the broker's development was completed, it was tested using the PowerTAC framework. The results were analyzed, and some adjustments were made to its architecture and strategy in order to increase performance before the participation in the real competition.

- **Participating in the real competition**

  The developed broker was submitted to the PowerTAC competition, so that it can test its strategies against other competing brokers. The results of this competition were then analyzed. Following the competition, its results and those of the simulation were be published.

Chapter 2

Literature Review

This section will present the review of the literature and of work previously developed by others that can be relevant to the work of this dissertation. This includes an explanation of what Smart-Grids are, and how they function, what kind of problems emerge from them, and some approaches to solve them. There is an analysis of the PowerTAC framework and competition, and of the strategies applied by participants in previous editions of the competition, followed by a section on Software Agents and Multi-Agent Systems. There is also a review of some of the Multi-Agent Platforms that exist and can be used in this work.

2.1 Smart Grids

All across the world, the existing power grids are becoming unable to answer the new demands of both consumers and producers [Far10]. The existing infrastructures are unable to accommodate the diversification of generation methods, incapable of offering a dynamic response to changes in demand, and are grossly inefficient, with levels of efficiency going as low as 30%, and energy production capacity being used at less than 80%, for 95% of the time.

While the rate of power transmission rises, and traditional models of consumption cease to apply, there is an increasing need for higher safety and security, since most critical services and infrastructures, such as transportation, finance, and communications, are mostly, if not completely, dependent on the reliability of the power supply [AW05]. Smart grids appear as a potential answer to the new challenges and requirements being imposed on energy markets and infrastructures. The smart grids are the next generation of energy grids. They furnish utility companies with complete visibility and control over the infrastructure, while being capable of mending themselves, and deal with irregularities in the system, without interruptions in the energy supply.

Since the source of most disruptions (90%) has been found somewhere in the distribution network, the adoption of smart grids must begin in that end of the chain, the distribution systems.

As such, the first changes towards the adoption of smart grids were made in the meter measurement technology with the creation of automated meter reading (AMR) in the distribution network. While this was a step in the right direction, it remains lacking on the main issue to be solved, energy management on the side of the demand. The AMR systems allow for the reading of data, but are unable to apply any measures as an answer to the data that is gathered, so are unfit to the transition towards a smart grid, that requires full control at every level.

Due to its shortcomings, AMR technology was not widely adopted. Instead, utility companies implemented Advanced Metering Infrastructure (AMI) systems that allow not only two-way communication, giving the companies full visibility over the grid, but also the imposition of local limitations on consumption, as a way to manage loads and costs [Far10]. Additionally, utility companies are reported to use the forward compatibility of AMI systems with the future smart grids as the main criteria of selection.

In [Far10], Farhangi states that smart grids are likely to evolve through the integration and interconnection of smart micrograds. Smart Microgrids are defined as groups of distributed energy systems, that are connected between themselves, and that are capable of functioning independently from the electricity grid. These microgrids are to include power generating capabilities, be able to handle various types of energy consumption profiles (industrial, domestic, office), and be equipped with communication capabilities and an intelligent core to manage all of its components. Additionally, it is stated that due to the high costs of immediately converting the whole electrical grid to one capable of accommodating the advent of smart grids, it is likely that the migration will be a gradual process of integrating smart grids with the existing ones. This means that smart grids will coexist and work alongside conventional electrical grids.

One issue that has been raised by utility companies, is that due to the current lack of uniformity in the AMI systems, the transition towards the smart grids will not be done without issues. The source of these issues is predicted to be the absence of communication protocols, interfaces and standards. As a response to this, there has been an effort to produce adequate standards. The ANSI C12.22 and the IEC 61850, related to smart metering and substation automation respectively, are examples of such standards.

2.2 PowerTAC

This section contains a review of the literature available about the PowerTAC framework and competition, including an in-depth analysis of the architecture and an overview of competitors in previous editions of the competition.

2.2.1 Architecture

PowerTAC is a smart-grid simulation framework with the objective of developing strategies for future energy markets based on smart-grids. The developed strategies are to be used by brokers, and created by the teams with the intention of them being competitive, in the regard that they must be able to attract customers. PowerTAC is also a competition of Trading Agents and the 2016 edition will be collocated with an important artificial Intelligence conference, IJCAI (International Joint Conference on Artificial Intelligence). In this competition, brokers, represented by software agents, compete with each other, testing the strategies previously developed by the several teams participating in the competition.

The main elements of the simulation are the energy brokers, the retail customers, the large energy suppliers, the distribution utilities, and the three different types of markets: the wholesale market, the balancing market and the tariff market.

The simulation time is organized in time blocks of one hour each. Each block runs in 5 seconds of real time, and every simulation runs for 2 hours of real time, meaning it spans over 60 simulated days. Because the clocks of brokers and simulation servers must be synchronized, they are installed on machines that use the Network Time Protocol, ensuring the synchronization runs smoothly.

The simulator is also responsible for keeping records of cash balances, customer subscriptions, and wholesale market positions of the brokers. Interest rates are included in the scenario. At the end of each simulated day, if the broker's balance is positive, it is paid the daily interest; if it is negative, it is instead charged the daily interest [KCW16]. Another component of the simulation is the availability of weather reports and forecasts. This information is made available to brokers on each time block, and is based on real world weather from a chosen location. The brokers can use this information to predict power consumption and production.

It is important to note that PowerTAC is organized in a client-server architecture, and that Server for the most part works as a black-box. Everything except the brokers is contained within the Server and inaccessible to the users, severely limiting the factors that the users can alter.

2.2.1.1 Brokers

Brokers are responsible for managing tariffs. On every time slot, there is a number of actions that they can undertake related to the tariffs. It is possible to offer new ones, adjust the terms and prices of existing tariffs (if the existing terms allow it) and restrict the energy consumptions of customers who subscribed to tariffs that allow it.

Brokers receive information about the game and other brokers. Some of this information is public, and is sent to every broker, and the rest is private and is sent individually to each broker [KCW16]. This information differs in the frequency in which it is delivered. Some is sent before the game begins to run, like game parameters, the identities of other brokers, customer records and bootstrap data of the weather and the markets. Every six simulation hours, brokers receive information about the wholesale market. Additionally, on every time slot, brokers receive data about the wholesale market, current weather conditions, and weather reports and forecasts for the next 24 hours.

2.2.1.2 Tariffs

Tariffs include a number of parameters including information about pricing, signup payments, early withdrawal penalties, hourly charges and so on [KCW16]. They can be modeled to have different rates for different periods of the day, consumption thresholds with different pricing, and to give the broker the ability to restrict power consumption of Customer's by a predefined amount. Dynamic pricing can be specified on a tariff, but the prices must be reported to customers beforehand. Each Tariff also specifies the type of consumption or production. These types are referred to as *PowerTypes* and can specify, for example, solar production, industrial or domestic consumption, among others.

Changes in tariffs are possible at each time slot, and starting this year, the withdrawal penalty to customers who are using those tariffs is set to zero, to avoid exploitation by the brokers of this feature. This change was shown to be necessary when in a previous edition one of the participants, AgentUDE, "locked-in" customers by abusing the tariff update feature. This is explained in more detail in a later section, dedicated to analysing the strategies of other competitors.

2.2.1.3 Customers

Consumers and producers of energy are both considered customers. Their behaviour is simulated according to a series of customer models. The interaction with the brokers is done through the tariff market, and the information about the customer in question is made available to the brokers at the beginning of the simulation. This gives the brokers knowledge about the type of customer (consumer/producer) they are dealing with, whether or not they have energy storage capabilities, and also the number of metering endpoints associated with each customer. This is important because customers with more than one metering endpoint might be subscribed to different tariffs, not necessarily by the same broker.

The customer models that are now available are divided between two main groups. The elemental customer model is focused on simulating the energetic behaviour of individual consumers, like households and office complexes. The factored model on the other hand is used to simulate the behaviour of larger groups of customers in face of a set of factors that influence their action.

The most significant action customers are responsible for, is the selection of tariffs. This is done through the analysis of the existing tariffs, and subsequent comparison and selection of the one with the higher utility value [KCW16]. The utility of a tariff is calculated based on a set of five parameters.

$$u_i = f(pv_i, pp_i, psignup_i, pwidthdraw_i, x_i) \tag{2.1}$$

The parameters represent, in order, the utility value of the tariff, the price of Kwh of the tariff, the periodic payment included in the tariff, the payment required to sign up for the tariff, the fee associated with an early withdrawal from the tariff, and and inconvenience factor, that represents the inconvenience associated with changing suppliers, and exists in every market, not just the energy one. The way each parameter affects the value of the utility is not exactly the same on every customer model due to differences in implementation. In addition to this, there is also an inertia value factored in. It relates to the likelihood of customers ignoring the tariff publication events, for considering it to be junk mail. This value is set to 0 in the beginning of the simulation and increases throughout the game, meaning that in the first time slots of the game, no tariff publication event is ignored, and that the likelihood of them being ignored, increases as the game progresses.

In the actual implementation of the simulation tool, the customers are very simplistic. They are only subscribed to one Tariff at a given time, and have only one PowerType throughout the simulation. The prosumtpion values are no affected by the tariff rates. Meaning that hypothetically, would the price triple, the consumption rate would remain unaltered. As such, the Tariff selection is the most important, if not the only action that the customers take, and as such, the Tariffs have a central role in the simulation.

Additionally, it is impossible for the user to select the customer models he will be using, as that is done by the server, without external intervention.

2.2.1.4 Markets

There are three different types of market present in the PowerTAC framework, with each having its specific use for brokers. They are the Customer Market, the Wholesale Market and the Balancing Market.

The Customer Market is where Customers interact with the energy Brokers. It is also referred to as the Tariff Market, since it is the place where tariffs are published. The way this market functions is simple, as was explained above. The brokers publish tariffs, and the customers evaluate and later select the ones that they find more suitable, in this case, being those with the higher utility value, according to Equation 2.1. It is important to reiterate that on this Market, both consumption and production tariffs are published, as Customers can be both consumers and producers of energy.

The Wholesale Market is an energy exchange. It functions as a periodic double auction. At this Market, brokers interact with energy generation companies, as well as with each other. There are two types of generation companies, called Windpark genco, and Grid genco. The first simulates a generation company based mainly on eolic generation plants on the same geographical area as the simulation scenario. Thus, it uses the same weather reports and forecast as the brokers. The second one simulates a group of production facilities, spread over various locations, the scenario geographical area being one of them. There is also a wholesale buyer, that simulates the behaviour of speculators and buyers in an aggregated way. An example given is an industrial plant that uses electric power when the energy price is low enough.

Brokers participating in the wholesale market can place future orders. The energy bought is delivered between one and twenty-four hours, in one of the time-slots that are enabled for energy trading. There is a minimum size to the orders, to avoid the spamming of the market by brokers.

Periodically, at the beginning of every time slot, the market is cleared. The process is done by the construction of supply and demand curves, from the orders previously submitted. The price where these curves intersect is the price selected to be the clearing price of the market. After this, bids that were higher than the clearing price are matched to asks that are lower than the clearing price.

The third Market present in PowerTAC is the Balancing Market. On the energy markets, it is essential that production and consumption are matched so that a balance is reached. At the end of every time-slot, brokers are expected to have a neutral balance of energy [KCW16]. This means they cannot sell more energy than they buy or produce. The Balancing Market can be used by brokers to achieve a zero-sum energy budget. However, the rates offered are far worse than what they would get otherwise, making this option undesirable.

2.2.1.5 Distribution Utility

The Distribution Utility operates the grid that is responsible for connecting the brokers and customers to the wholesale market. It is also the "default broker", that offers default tariffs with which broker tariffs will be compared [KCW16]. Since the management of the grid requires maintenance, the Distribution Utility recovers the investment by charging fees.

These fees come in two types, Distribution and Transmission Capacity Fees. The Distribution fee comes in the form of a fixed payment per time-slot, to be made by the consumer, and its value is divided between small consumers, like households and offices, and big consumers like industrial plants and hospitals. The Transmission Capacity is paid by the brokers. Its value is related to the contribution of each broker customers to peak demand times.

2.2.2 PowerTAC Available Information

During the simulations done with the PowerTAC framework, the simulation server sends a number of messages to the participating brokers, with information relative to the current state of the competition. The messages arrive at different intervals, with different degrees of importance, some being only in respect to the broker, others being public domain information (see 2.1).

2.2.3 PowerTAC competitors' strategies

This section will be referring to the strategies of competitors in PowerTAC competitions. In [Pro13] the author provides a compilation and analysis of the strategies used by the competitors in 2013. He also states, however, that due to the complexity of the applied strategies and the resistance from developer teams to make public all the details of their strategies, the chapter of [Pro13] related to the strategy analysis is only an introduction, rather than an in-depth analysis.

- **Mertacor**

  Mertacor's main focus is stated to be the creation of optimal tariffs. It uses a Particle Swarm Optimization algorithm to estimate variables that in some way, will influence the publication of new tariffs [TKM06]. The variables estimated are not mentioned by the author. Mertacor also applies an Exponential Smoothing Algorithm to predict the load of customers

Table 2.1: PowerTAC Available Data

Name	Type	Frequency	Description
Game Parameters	Public	Once in the beginning	Contains the parameters used to configure the game soon to start.
Broker Identities	Public	Once in the beginning	Arrives at the beginning of the simulation. Contains the Identities of all participants in the simulation.
Bootstrap Customer Data	Public	Once in the beginning	Contains the records for customer activities (consumption and production) during the Bootstrap Period.
Default Tariffs	Public	Once in the beginning	Contains the specification of the Tariffs offered by the default broker. This information is frequently used by participants as a reference to the creation of new tariffs.
Customer Records	Public	Once in the beginning	Contains information about each customer present in the game, such as the type of consumption or production and the number of metering endpoints.
Bootstrap Market Data	Public	Once in the beginning	Contains information about the prices and amounts of energy traded in the Wholesale Market during the Bootstrap period.
Bootstrap Weather Data	Public	Once in the beginning	Contains the Weather,Reports for the Bootstrap Period. Each has the values,for the Temperature, Cloud Cover, Wind Speed and Wind Direction.
Wholesale Market Clearing Data	Public	Every timeslot	Contains price and quantities for energy traded in the Wholesale Market in the previous timeslot.
Wholesale Market Order Book	Public	Every timeslot	Contains the asks and bids on the Wholesale Market that were not cleared during the last timeslot.
Total Consumption and Production	Public	Every timeslot	Contains the net total for energy,consumption and production across all of the simulated environment.
Weather Report	Public	Every timeslot	Contains the Weather Report for the,previous timeslot, including the value of Temperature, Cloud Cover, Wind,Speed and Wind Direction.
Weather Forecast	Public	Every timeslot	Contains the Weather Forecast for the next,24 timeslots including the value of Temperature, Cloud Cover, Wind Speed,and Wind Direction for each slot.
Tariff Transactions	Private	Every timeslot	Contains data about how much energy and funds were traded with each customer, subscribed to the broker's tariffs.
Balancing and Distribution Transactions	Private	Every timeslot	Contains the values of the transactions,made in the Balancing Market, and the charges made by the Distribution Utility.
Wholesale Market Transactions	Private	Every timeslot	Lets the broker know which of his Wholesale Market orders were cleared in the previous slot.
Wholesale Market Positions	Private	Every timeslot	Notifies the broker about his open positions in the next 24 slots of the Wholesale Market.
Cash Position	Private	Every timeslot	Informs the broker about his cash balance in the bank.
Tariff Updates	Public	Every 6 timeslots	Arrives once every 6 timeslots. Contains information about new Tariffs,that are available, old Tariffs that were revoked, and current Tariffs,that have been altered.
Tariff Updates	Private	Every 6 timeslots	Contains information about new subscriptions to tariffs, and customer that have abandoned it.

in the following time-slots. The main goal of the agent is to maximize revenue. Mertacor participated in every edition of the competition, from 2013 to 2016.

- **CrocodileAgent**

  CrocodileAgent has different strategies for the customer and the wholesale market, and aims to have the best performance in both. On the customer market, maximal profitability is attempted, through the offer of tariffs based on predicted energy consumptions, and adaptations of those tariffs whenever the customers change providers. When in the presence of competing agents, CrocodileAgent's method of action is to offer tariffs that are more competitive. It learns and adapts to market trends, and continually offers improved tariffs [Tal+13]. The focus of the strategy for the wholesale market is to use the balancing market as little as possible. Several different strategies are stated to be used, but are not mentioned. This agent's general strategy is balanced, focusing on all relevant markets, and still offering competitive tariffs. Crocodile Agent participated in every edition of the competition from 2013 to 2016

- **MLLBroker**

  MLLBroker uses Gaussian processes to forecast demand, using all available information, including the weather. The prediction method was built by the team, and the main objective of the agent was to test said prediction method [KCW14]. Profitability is not as competitive as on other brokers, due to the narrow focus on demand prediction. MLLBroker participated in the 2013 edition of the competition.

- **AstonTAC**

  AstonTAC makes use of Markov Decision Processes to assist in energy purchases. Energy prices are predicted through a Non-Homogeneous Hidden Markov Model. The predictions are used to purchase cheap energy from the generation companies. Its approach to the balancing market is to try to maintain the energy budget balanced, thus avoiding as much as possible to use the balancing market [CHL10]. AstonTAC focuses mostly on its prediction abilities. AstonTAC participated in the 2013 edition of the competition.

- **TacTex**

  TacTex focuses on the utility of tariffs [US14]. It estimates the long run utility of the possible tariffs, and builds them with the target of maximizing the utility value. The strategy on the wholesale market is built to decrease costs, in orders to increase profits. Lastly TacTex applies machine-learning algorithms to estimate variables that it considers important. The estimated values mentioned in the paper are the demand, supply and other essential costs. TacTex participated in the competition every year from 2013 to 2015.

- **AgentUDE**

  On their paper [ÖU15], Özdemir, and Unland analyse the strategies of AgentUDE, the winner of the PowerTAC final on 2014. The analysis is divided mainly between the agents actions in the different markets. On the Wholesale market, AgentUDE uses Adaptive prediction techniques. The price estimation is done in two stages, the base and the final. This prediction based strategy allowed AgentUDE to achieve the second best performance in the Wholesale Market. AgentUDE's approach to the Customer Market was to publish tariffs with the lowest value. The price of energy on AgentUDE's tariffs is the lowest of the competition, but the benefit to the consumers is diminished by high early withdrawal fees. As the competition progressed, competitors were forced to publish more attractive tariffs, making the customers switch from AgentUDE to the competitors, and pay the early withdrawal fees. In the end of the game, these fees were responsible for 20% of the cash received. This strategy is stated to not work well unless it is being used against competitors that are capable of offering competitive tariffs of their own, so that the customers decide to change their tariffs and pay the fees. Regarding the Balancing Market, AgentUDE bases its actions on prediction once again. By using the previous consumption data of customers to make predictions with. Since these predictions are not considered reliable, due to a number of changing factors, the value is added to the signal received from the balancing market, and then the orders are placed. AgentUDE managed to be the second broker to pay less to the balancing market. AgentUDE participated in every edition since 2014 (2014, 2015, 2016).

- **TugaTAC**

  TugaTAC is a broker agent that makes use of fuzzy systems [RQ15]. Its main focus is on the retail market, creating and updating tariffs, by applying fuzzy logic rules to the results of previously published tariffs. It was developed in 2015 by Thiago R.P.M. Rúbio and Jonas Queiroz, and is the precursor to the broker that was developed in this work.

- **CwiBroker**

  CwiBroker uses different strategies depending on the number of competitors in each game [LHL14]. For duopoly games, it applies a modified Tit-for-Tat strategy, and for oligopoly games, it predicts the profit potential of a set of Tariffs with the use of regression analysis to make predictions. Its strategy fr the wholesale market is based on the principles of equilibrium in continuous auctions. It participated in both the 2013 and 2014 editions.

2.3 Multi-Agent Systems

2.3.1 Software Agents

In [JW96] the authors define a Software Agent as an autonomous program, capable of perceiving the environment in which it is inserted, and adapting its actions depending on its objectives. Three different levels of agent complexity are mentioned. The lowest level of complexity contains agents that follow pre-defined rules to perform simple tasks. The second level of agents perform tasks at the request of a user. The last level of agent complexity, contains agents that are referred to by the authors as “predictive”. Agents in this category perform tasks such as constantly monitoring news sources online, and inform the user of the ones that the user is likely to have an interest an in.

In addition Agents are said to share a number of characteristics that distinguish them from other categories of software engineering and development. Those characteristics are Autonomy, Social Ability, Responsiveness, and Proactiveness. This means Software Agents should be able to handle most of their problems and changes in the surrounding environment without the intervention of humans, interact with humans or other agents, and not only respond to changes in circumstances, but have goals of their own, and behaviours to reach those goals, to be applied when appropriate. Agents can also be divided accordingly to different models, as follows:

2.3.2 BDI

The superior results of agent-based software systems in the handling of various dynamic and complex situations, has lead to developments and improvements on their design. A number of paradigms and alternatives for the construction of these systems has emerged throughout the years. One of the approaches, commonly known as the BDI architecture, is to model agents based on a set of Beliefs, Desires, and Intentions. According to [R+95], the Beliefs of an agent can be represented as a data structure, a variable or a set of expressions, and represents the likely state of the environment as observed from the point of view of the agent. The Desires of the agent are related to the objectives, goals, and priorities that should influence the behaviour of said agent. Wooldridge states that the Desires do not have to be achievable, stable, or coherent with one another. The example of human agents with contradictory desires is given to support this point. [Woo97] Finally, as a way to accommodate potential fast changes in the environment, the authors propose the Intentions, that represent the course of action currently selected by the agent.

2.3.3 FIPA

FIPA stands for Foundation for Intelligent Physical Agents. It is an organization associated with the IEEE Computer Society that is responsible for developing standards for technology based on software agents. It builds standards on several areas of agent-based technology, such as agent communication, agent management and agent integration with other software or human actors. In the Agent communication field, FIPA is responsible for developing the ACL, Agents Communication Language. The ACL is based on ARCOL, an already existing language, that was chosen instead of the KQML (knowledge querying and communication language), since it was more expressive and semantically well defined. [ON98]

The ACL language can be divided in five different layers. The first layer is the protocol. It defines the structure and rules for the communication. The layers two to five, are contained in each ACL message traded between agents and are, in order, the communicative act, the messaging, the content language, and the ontology. The communicative act is the definition of the type of communication being made, such as a request or an announcement. The messaging contains information about the message, like the identities of the sender and receiver and the context in which the message is sent. The ontology defines the meaning of the terms used in the content of the message.[ON98]

2.4 Multi-Agent Platforms

There exist a number of different multi-agent building frameworks and platforms. There is not however, one that is accepted as being superior to the others. The objective of this section is to bring light on some of the existing platforms, and in the end, explain the one that will be used during the development of this work.

2.4.1 Netlogo

NetLogo is a simulation environment for the development of agent based systems. It is also a programming language for those type of systems. It was built so that it is useful both for education and research, not being too complex, so that novice users are able to experiment with and use it. The language is of the LISP family, and is a mixture of two other languages, StarLisp and Logo. NetLogo adds concurrency and agents to Logo. The agents are seen as "turtles", that move in a virtual world composed of "patches". Both the turtles and the patches can be altered by the user, and according to the authors have been turned into muscles, cars, birds, trees, walls and waterways, depending on the objective of the user. [TW04]

2.4.2 Repast

Repast is a Java based software framework for the simulation of agent-based scenarios. It includes tools to visualize and capture data from the simulations. The events of the simulation are organized and scheduled according to "ticks", that serve simply as triggers for events. Repast first emerged as a way to simplify the Swarm simulation framework, but that goal was abandoned quickly, due to a number of reasons. The development of Repast continued in the University of Chicago. The design of Repast was made to allow for a short learning curve and robustness. Additionally, the creators concerned themselves with future development and with the performance of the simulations, adopting a "good-enough" performance goal. [Col03]

2.4.3 Jade

JADE (Java Agent Development framework) is a FIPA-compliant framework for the development of software agents. According to the FIPA specifications, the JADE platform is managed by system agents. All the communication between agents is done through message exchange between the agents, using the FIPA-ACL language. [ON98]

It is also a Distributed Agent Platform, as it can be split over different hosts. Software agents in developed in JADE are said to be autonomous and social. This means that agents actions are not restricted to reactions to external stimuli, and also that the agents have the ability to interact with other agents with the objective of achieving its objectives. [BPR01]

2.5 Summary

This review provided insight on existing work that is relevant for the context of this thesis. The most important points are related to the strategy analysis. Some gaps in the strategies used in previous competitions were identified, and the use of a Multi-Agent System seems to be a promising option to address these gaps that is worth exploring. Regarding the Multi-Agent Platforms, JADE will be used to create the MAS, since we need to combine our approach to the PowerTAC platform.

Chapter 3

Architecture and Models

As briefly explained in the introduction, the main problem to be addressed in this work will be the creation and update of tariffs. Tariffs need to be competitive, in the sense that they need to be attractive to customers, providing low prices or other advantages, but still be profitable to the brokers that offer them. The way to do this is at the discretion of the broker, and different strategies are applied.

Assuming that in real life cusotmers choose the best tariff regarding the information they have in hand, Ketter *et. al* [KPC13] discussed and applied a utility-based model for customers on market simulations. The utility value of a tariff is calculated according to a formula that uses a set of parameters associated with each tariff.

$$u_i = f(pv_i, pp_i, psignup_i, pwidthdraw_i, x_i) \tag{3.1}$$

The objective then, is the creation of a system that is capable of effectively addressing the tariff management and creation problem, by creating competitive tariffs, and adjusting them as necessary. Following our hypothesis, our beliefs indicate that a multi-agent approach could result on better tariff composition, since we could create specialist agents to handle the information available and help composing the tariff. In order to better explain this idea, an architecture for our MAS is proposed in the next section.

3.1 Multi-Agent Architecture

The proposed solution for the problem is the implementation of a Multi-Agent System, that is capable of tackling the tariff creation problem. The strategies of most participants in the PowerTAC competition have fairly narrow focuses. Some focus only on testing prediction methods, or use decision processes to assist in energy purchases. This means that most competitors ignore part, if not most of the information that is made available, and thus their strategies do not perform at their highest possible level.

The use of a Multi-Agent System will allow the focus of the strategies to be broader, and hopefully produce superior results compared to other narrower strategies. The system includes

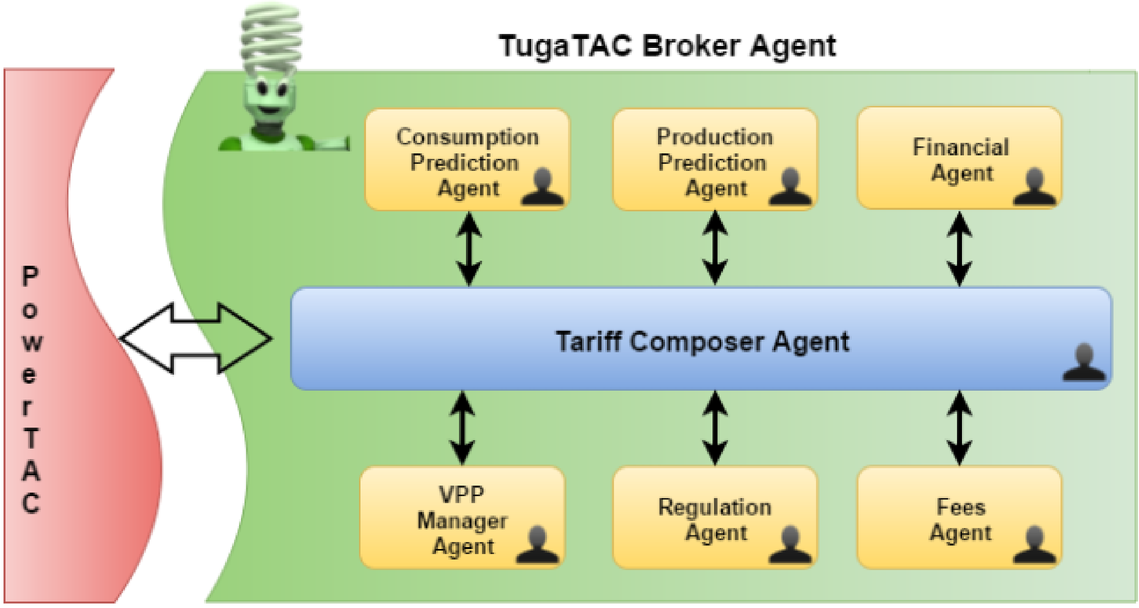

Figure 3.1: A inner MAS architecture for a PowerTAC broker agent

agents dedicated to the prediction of consumption and production, financial analysis, among other possible features.

Figure 3.1 presents our proposed architecture for a PowerTAC broker agent. The PowerTAC framework allows us to create an individual software broker that will interact with the PowerTAC interfaces through the system's API. In this sense, we developed a MAS inside the broker's model. We believe that each "intention" of the broker can effectively be represented by a specialist agent that handles a specific type of information, such as weather agents that focus on dealing with prediction models.

Thus, each specialist agent can communicate its solution to a central control agent, responsible for tariff decision. The central agent takes the results from other agents into consideration and decides the final set of tariffs to be publish on the PowerTAC market.

In order to develop the described architecture important considerations should be done, namingly regarding the energy market features, prediction and negotiation models, as well as learning mechanisms to achieve the better results. These features are better discussed on the next subsections.

3.1.1 Improvements on TugaTAC

The new Broker was a continuation of the development of TugaTAC, previously developed by Thiago Munhoz. The main change that was made was the addition of the Multi-Agent System, that will be described in the next sections. The modules responsible for the exchange of messages with the server were mostly left unchanged, except for the alterations needed to redirect the incoming messages towards the developed MAS.

3.1.2 Architecture Layers

The Multi-Agent System that was developed is divided between two main layers, each with their own purpose: the Specialist Layer and the Manager Layer. These layers were created as a way to more easily define the function of each agent, and to facilitate the building of the communication protocols.

One of those layers is the Specialist Layer. The software agents that manage information that comes from the PowerTAC simulation should be in this layer. The function of the agents in the specialist layer is to receive the data and handle it. After the data has been handled properly, the specialist agent broadcasts a message to the network of agents, specifically to the other layer where it will be used.

Since the Specialist Layer is the way in for all the information to the system, sometimes the function of the agent is to merely relay the messages it receives to the Manager Layers. This occurs with information such as the ID of the broker, or info about existing Tariffs. Although information about the Tariffs can be analysed and value taken from it, it is also essential to know the current state of the market in order to make an educated decision.

The other Layer is the Manager Layer. This layer contains the agents responsible for proposing Tariff related operations, such as tariff submission, revoking and even updating. The agents in this layer communicate exclusively by receiving messages from the Specialist Layer and sending messages to the Decision Agent. It is in the Manager Layer that Tariffs are composed. The agents in this layer do this by using the information received from the Specialist Layer, including predictions of future prices, consumption and production values. After the Tariffs are composed they are sent to the Decision Agent.

The Decision Agent, while being part of the Management Layer, works differently from the other manager agents, effectively working as a third architecture layer.

3.1.3 Agents

This section will contain a description of each Agent developed during the work and included in the broker. They are divided, as they are in the architecture, in two groups, depending on which layer they belong to.

3.1.3.1 Specialist Agents

These agents are included in the Specialist Layer of the Architecture. As stated before, the function of these agents is to handle the incoming information from the Server, analyse it, and relay the results to the Manager Layer. They provide the entry point for all the information in the Multi-Agent System.

- **Wholesale Agent**

  This agent focuses on the data available about the Wholesale Market. Once every timeslot, it receives the post-clearing orderbook, and information about cleared orders and bids. It

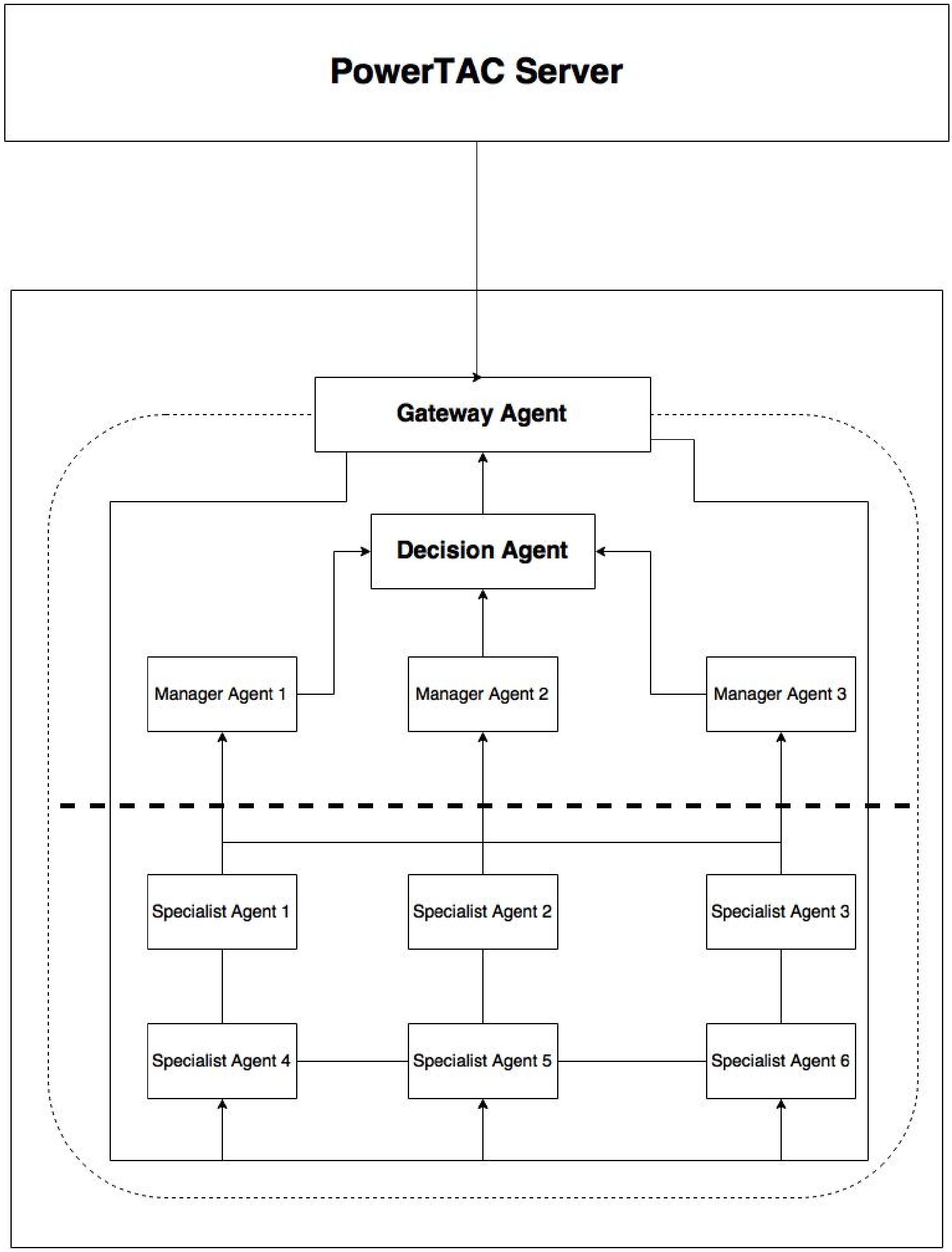

Figure 3.2: The MAS Architecture that was developed

also has access to the broker's open commitments on the market for the next simulated day (24 timeslots).

The Wholesale Agent keeps a record of previous clearing prices on the wholesale market, and makes a prediction on the price for the next timeslot, based on the prices of the previous timeslots. This prediction is then sent to the Manager Layer, that will use it to compose Tariffs.

- **Prosumption Agent**

  The main goal of the Prosumption Agent is to monitor the values of consumption and production on the market. On the beginning of the simulation it receives consumption and production data about every customer during the Bootstrap Period. After this, it receives once per timeslot every Tariff Transaction made regarding the broker's own Tariffs. Based on this information, the agent makes a prediction for the values of consumption and production in the next timeslot, and sends it to the Manager Layer

- **Tariff Agent**

  The function of this agent is to monitor the state of the Retail Market, by keeping a record of the Tariffs, both the ones that are active and the ones that have been revoked. The initial objective was to analyse this Data and draw value from it, but since no effective way was found, this agent was kept solely as a purveyor of Tariff Information to the Manager Layer.

- **Other Agents**

  During the development, other specialist agents were proposed, but since they were not functioning properly, or their function not properly defined, they were not included in the final broker. Such Agents were

  – **Weather Agent:** The function of the Weather Agent would be to make predictions for production and consumption based on the Weather. It would use the Weather Reports and Forecasts, and together with previous data for prosumption, predict future values. The proposed Weather Agent was making predictions using Machine Learning techniques, but even though the results were positive, when compared to the other, simpler prediction techniques, they were not good enough to justify being included in the final broker.

3.1.3.2 Manager Agents

These are the Agents included in the previously described Manager Layer. They receive info from the Specialist Layer and use it to compose Tariffs and create recommendations that they then send to the Decision Agent.

- **Tit 4 Tat Agent**

This Agent creates Tariffs based on a slightly modified replication strategy. Upon receiving a Tariff from the Specialist Layer, it replicates it, with a slight increase in utility. The increase in the utility is done with a decrease in the Tariff Rate. This process is done as long as the received Tariff was not published by the Broker. The Tariffs created in this way are then sent to the Decision Broker.

- **Simple Prediction Agent**

  This Agent uses the predictions sent in by the Wholesale and Prosumption Agents to compose Tariffs. It uses this values to create a Tariff with the highest utility possible, but that is still profitable. The principle used to calculate the potential profitability of each Tariff is the one present in the next formula:

$$CPrice * P > P_p + T_p * P \tag{3.2}$$

  The *CPrice* parameter represents the projected clearing price on the Wholesale Market, the *Prosumption* represents the projected Production, or Consumption. The *PPayment* represents the Periodic Payment associated with the Tariff being evaluated, and the *TRate* parameter is the Rate associated with the Tariff.

3.1.3.3 Decision Agent

This is the Agent responsible deciding which Tariffs will be published and revoked. It receives the proposed Tariffs from the Manager Agents, and evaluates them according to its own utility function, that takes into account the Profit Potential of each Tariff, and the projected utility for the customer (see figure 3.3). It analyses the existing Tariffs for each Powertype, and if one of the proposed Tariffs is better, it revokes the first one and publishes the latter. The decision is made using a decision model that will be explained in more detail in a following section.

3.2 Integration with the JADE Framework

The Multi-Agent System that was developed was built using the JADE Framework. JADE was integrated in the project as an extension to the original broker. This next section will elaborate on some topics regarding the way that integration was made.

3.2.1 JADE Gateway

One of the issues faced while trying to integrate a JADE based system in an already existing application, was how the JADE environment would communicate with the outside environment, that in this case is the PowerTAC Environment. This was finally achieved with recourse to the JADE Gateway implementation. The JADE Gateway receives Jade Behaviours and passes them to the Gateway Agent inside it. After the Behaviour is executed, it is possible to retrieve the results.

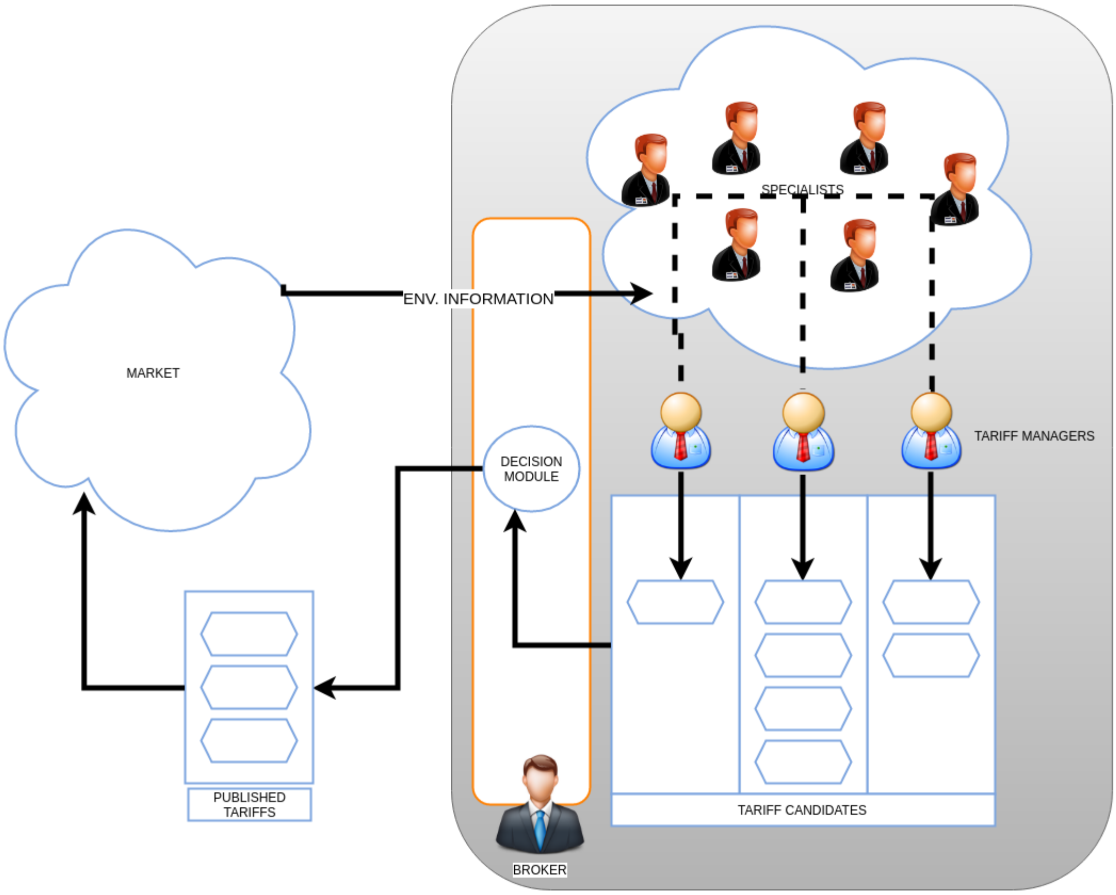

Figure 3.3: The role of the Decision Agent

This is used in the project to exchange information from the outside application with the agents inside the JADE Environment.

This was achieved with the implementation of two JADE behaviours, one to exclusively send messages with information to the Specialist Layer, and the other one to issue requests to the Decision Agent. Both Behaviours broadcast an ACLMessage with a defined topic. The topic of the message lets the receiver now which messages are for him, and how to manage the content. This is known as Topic-Based Communication and will be explained in later section. The content of the ACLMessages is an object of the MessageContent class that is extended by several other classes, depending on what information it is supposed to carry. The actual classes that are sent in the ACLMessages are divided between Internal and External Messages.

The implementation takes advantage of the possibility of extracting a result from JADE behaviours. This is specially useful in the behaviour used to request information from the Multi-Agent System. It simplifies an otherwise troublesome task.

3.2.2 Topic-Based Communication

In order to make the task of sending and receiving messages simpler, all the communication is done through the use of Topic-Based Communication. This differs from regular agent communication because instead of sending a message to one or more specific agents in the system, which requires the sender to know which agents currently exist in the system, the sender broadcasts a message with a given topic, and every agent that has subscribed to that topic receives it.

So in the beginning, every agent uses the topic service to subscribe to the types of messages it wishes to receive, and when they are broadcasted, the JADE framework places them in the message queue of the agents that are subscribed to that topic. Perhaps the biggest downside of this approach is that in an open environment, it is possible for ill-intentioned agents to "eavesdrop" on the messages sent by every other agent, but since in this case the environment is closed, that is not a serious problem. Like it was stated before, the communication is organised by splitting the messages between two groups, Internal and External Messages.

- External Messages: In this group is every message type that comes from, or goes to, the outside environment. Includes every piece of info that arrives from the PowerTAC server, and the answers to the request made to the decision agent. Only the Specialist Layer and the Decision Agent have contact with the message types in this group.

- Internal Messages: Every message type exchanged between the agents in the system, that does not interact with the outside world is in this group. It includes the messages sent from the Specialist Layer to the Manager Layer, and from the Manager Layer to the Decision Agent. With the exception of the message containing the BrokerID, the Agents in the Manager Layer interact exclusively with messages in this group.

3.3 Decision Model

The objective of the Decision Agent is to select the group of Tariffs with the highest value of Utility. In this case the utility is calculated from the point of view of the broker, but takes into account the utility for the customer as a way to predict the Tariff adoption rate.

In a more complex scenario, where the same customer might be subscribed to different tariffs at the same time, the selection process would have to take into account how each tariff affects the utility of the others, meaning that the Utility of a group of tariffs would not necessarily be equal to the sum of the Utility of the Tariffs it is composed of. However, since so far the implementations of the customer models are not that intricate, each customer is subscribed to only one tariff at any given time. This means that as long as the broker does not offer various tariffs for the same type of prosumption, and there is no reason why it should, there will be no conflicting tariffs.

The reason why there should be only one Tariff offered by prosumption type is that even if various tariffs are offered, only one of those is the best, so the customers will select that one, and the broker has no interest in maintaining the others.

So since there are no conflicting tariffs, and there should only be one Tariff for consumption or production type, the Utility of a group of Tariffs is equal to the sum of its parts, meaning to the sum of the Utility value of each composing Tariff. As such, the problem is much more simple and the selection process is conducted considering individual Tariffs for each power type instead of considering groups.

At the beginning of every round the Decision Agent evaluates every Tariff, and makes decisions based on the results. To begin, it revokes every current Tariff the he no longer deems to be lucrative. After that, every Tariff is Evaluated and for each Power type, the Tariffs with the highest perceived value are sent to the broker to be published, as long as they are not going not be competing with already existing tariffs from the same broker.

What this means is that the Decision Agent only replaces his own Tariffs by more competitive ones, if another competitor has the market lead. If the best Tariff in the Retail Market for a given Power Type has been published by the broker, no action is taken.

The Tariff Evaluation algorithm works as follows:

- For a given Tariff, its value is calculated based on its profit potential, projected subscription rate and on a Trust Factor, that is related to the creator of the Tariff. An agent that uses a simple replication technique has a lower Trust Factor than one who uses more complex techniques.

- If the profit potential is negative, the Tariff is no longer considered and the value is the minimum possible. There is no point in entertaining Tariffs that are bound to be unprofitable, it is more beneficial to the broker to offer no Tariffs and trade no Energy than to continuously lose money with losing trades.

- If the profit potential is positive, the tariff value is the sum of the profit potential and the likelihood of being subscribed to, multiplied by the trust factor.
- Every Tariff is evaluated in this way

This procedure seeks to ensure that the broker always offers the most competitive Tariffs in the market, as long as it can do that and still maintain profits.

3.3.1 Formalization

When being analyzed from the broker's point of view, the value of the tariff is given by the following formula

$$Value = Rate_T * Production_p \tag{3.3}$$

The parameters in equation 3.3 represent in order, the value of the tariff for the next few timeslots, the Rate associated with the tariff, and the Projected production for the next timeslots.

The decision agent uses this tariff value to calculate the value of the set of tariffs. As explained before, the value of a set of tariffs, equals the sum of the value of the n tariffs it contains, as seen in equation 3.4

$$SetValue = \sum Value_n \tag{3.4}$$

What the decision model does is compare every possible set of tariffs, and select the set n that for every i makes the comparison in equation 3.5 true.

$$SetValue_n \geqslant SetValue_i \tag{3.5}$$

Since the set with the highest value is the one containing, for each type of energy prosumption, the tariffs with the highest value, formula 3.5 can be expressed as follows.

$$\sum Value_n \geqslant \sum Value_i \tag{3.6}$$

The comparison present in equation 3.6 means that the broker must find the set with the highest value, by comparing the sums of the values of the tariffs that contain them.

3.4 Summary

This chapter explains the architecture of the solution that was developed as an answer to the problem. It consists in a Multi-Agent System, composed by a set of specialized agents, that will focus on analyzing information related to their area of expertise and then supplying the tariff managers with recommendations for the tariff creations. The managers then compose the tariffs and send them to the decision agent that selects the best set of tariffs to be published.

The selection of the tariffs to integrate the set is done according to the decision model that is detailed in the previous section. The core principle of the model is that form the point of view of the broker, the value of the tariff set, is equal to the sum of the tariffs it includes.

Chapter 4

Experiments and Results

This chapter contains the results of the experiments conducted throughout the work. The first section describes the local experiments, the second describes the remote experiments, specifically the participation in the PowerTAC 2016 edition, and finally, the last section contains an overview and analysis of the results. On the pictures and graphs, our broker is identified as TugaTAC.

4.1 Local Experiments

This section contains the results of those experiments that were performed locally. In these experiments, our broker competes against other brokers, that participated in previous editions of the competition. They are made available by the development teams in the Broker Repository of the official PowerTAC wiki.

4.1.1 Against Default Broker

The developed broker was tested locally against the default broker several times. The results were very similar in all of the simulations with the Broker winning every time with a significant lead, both in profits and in market share as seen in figure 4.1.

Generally the Broker was able to reach about 20 Million in profit, and the Default Broker would finish at about 9 Million. Even though the results in the wholesale market were not positive, in the end, the retail profit was enough to offset the loss.

4.1.2 Against CwiBroker

In the game against the CwiBroker the results were not positive. Both the CwiBroker and our own were unable to maintain positive cash balances, even while being the only ones trading energy (see figure 4.2). In this game, the broker strategy to increase market share worked, with the broker having over three quarters of the retail customers (see figure 4.3). However, due to the poor wholesale strategy, the profits are hindered by the heavy fines imposed by the balancing market.

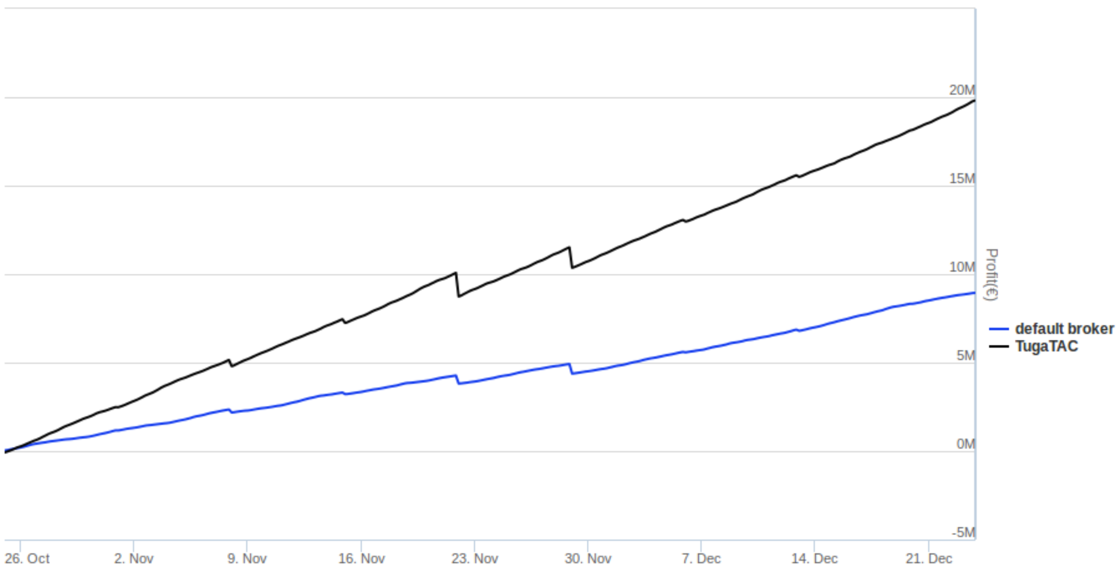

Figure 4.1: Sample result for a Game against the Default Broker

From the results we can gather that CwiBroker also does not have a good overall strategy, since it is also not able to maintain profits, as seen in . The Default Broker is the only one that does not present negative results, since it has no customers and does not trade energy.

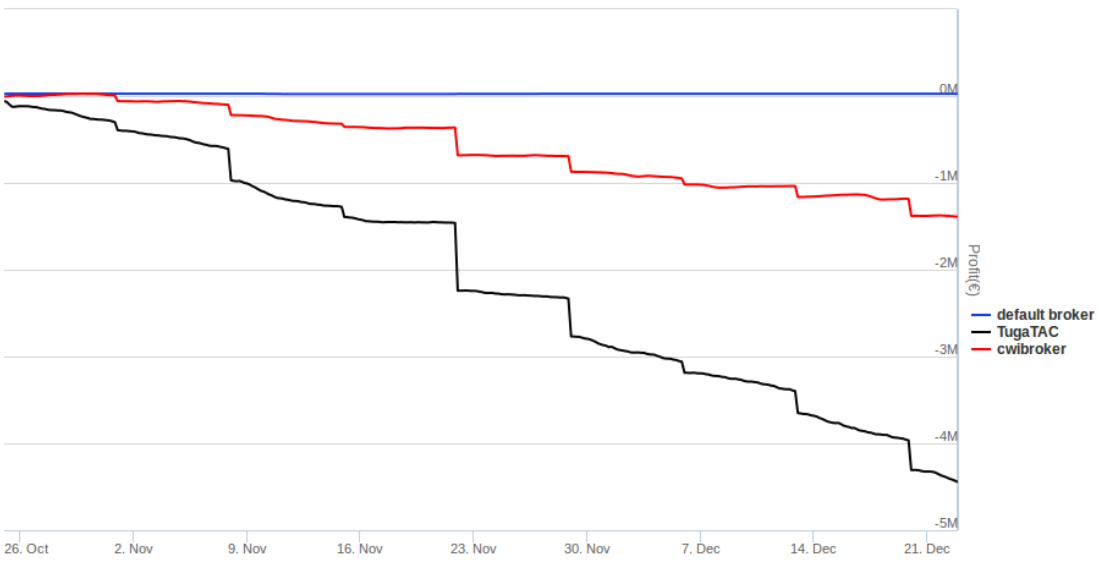

Figure 4.2: Result of a Game against the CwiBroker

4.1.3 Against AgentUDE

This was the only local experiment in which the participating brokers were able to finish with profit. However, the Default Broker still came out on top, with far more money than either competitor (see image 4.4). In this simulation, on the balancing events, the cash balance of our broker

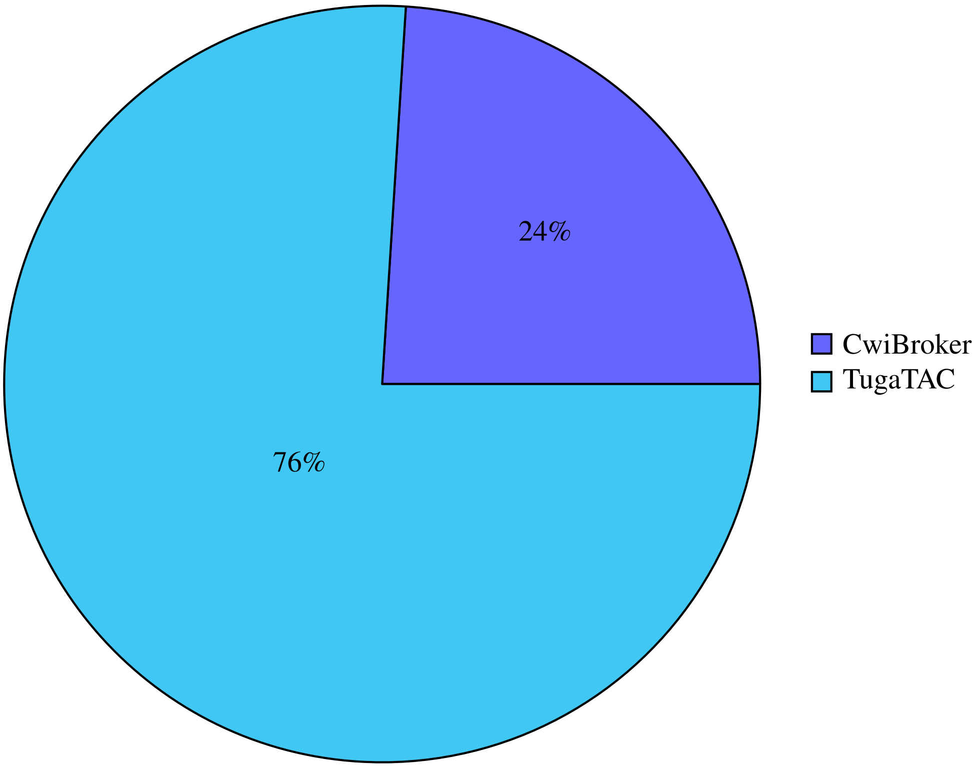

Figure 4.3: Market share distribution in a game against CwiBroker

goes slightly up, while the others go down, showing that in this instance, the energy imbalance was positive, meaning the broker bought more energy than it sold.

This experiment is specially interesting, because AgentUDE, the winner in the 2014 edition, was here unable to defeat the default broker. This shows that the interaction between different strategies is far more intricate than it would appear.

4.1.4 Against CwiBroker and AgentUDE

The results on this game were even worse than on previous games. The market share obtained was negligible (as seen on image 4.6), and yet, the loss was substantial (see figure 4.5). It is likely because even though there are close to no customers subscribed to the broker's tariffs, those that are, are producers, so the broker buys energy at a steady pace. Normally, the energy bought is either sold to other retail customers, or is sold in the wholesale market. Since there are no consumers willing to buy, and the wholesale strategy is defective, it is understandable where the losses come from.

It is also noteworthy, that no agent was able to maintain a positive balance. The reasons for this have not been properly identified.

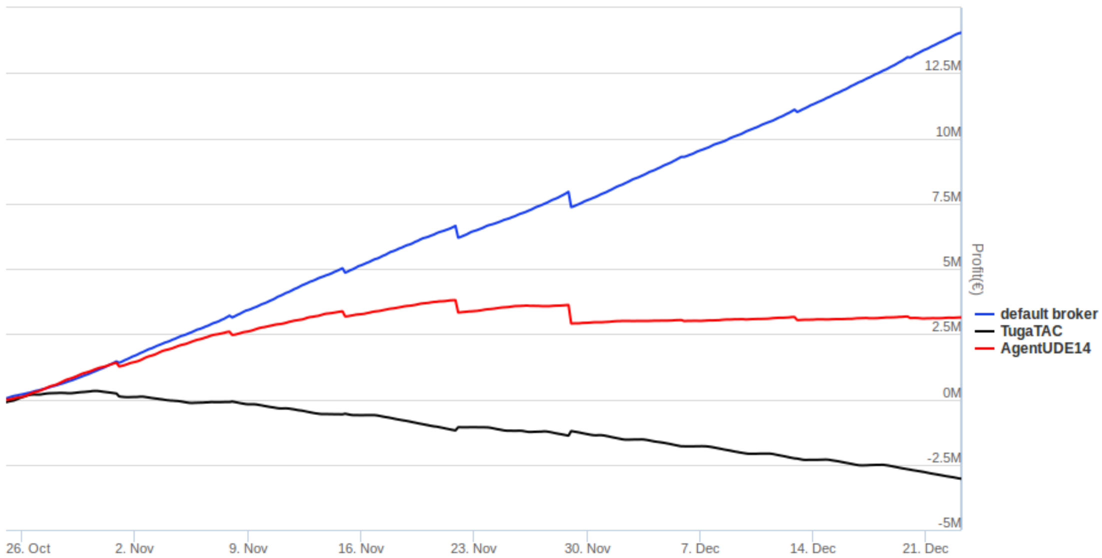

Figure 4.4: Result of a Game against AgentUDE

4.1.5 Observations and Critics

The results obtained were not as positive as expected. The only scenario in which there is a consistently positive result is when competing solely against the Default Broker.

Against CwiBroker, the final result was negative for both participants, and when competing against both CwiBroker and AgentUDE, all agents finished the game with negative cash balances as seen in figure 4.5. When trading against the Default Broker and AgentUDE, both other agents were able to make a profit, while our own broker also finished with a negative balance.

On every game there are moments, visible in the charts 4.1, 4.2, 4.4 and 4.5 , where the balance of each participant drops abruptly. It is visible on every chart,starting at around 1 Nov (simulation date) and occurs every 7 simulation days (8 Nov, 15 Nov, 22 Nov, 29 Nov, 6 Dec, 13 Dec, 20 Dec). This occurs at the same time for all participants on each game, and is caused by balancing events. The fact that almost every time participants lose money, shows that they are generally unable to maintain energy neutral portfolios, always selling more than they buy.

It is also visible that whenever there is more than one participant, the Default Broker takes the upper hand. This stands opposite to what would be expected. The Default broker is built with low complexity, and was developed to be a placeholder, not a real competitor. This might point towards the fact that complex strategies might not necessarily be better, but the event requires further study before a statement can be made.

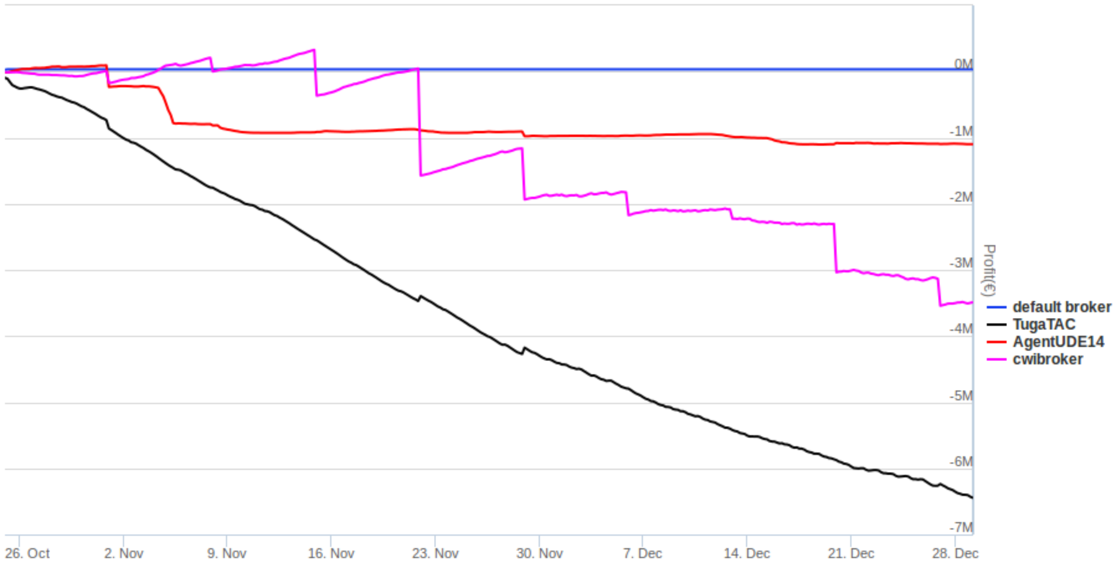

Figure 4.5: Result of a Game against CwiBroker and AgentUDE

4.2 Remote Experiments

This section will provide details about the participation of the developed broker in the PowerTAC competition.

4.2.1 Tournaments

The PowerTAC 2016 tournament was divided in three phases: the Qualification Rounds, the Seeding Rounds, and the Finals.

- **Qualification Rounds**

  The Qualification Rounds happened between the 17th and the 25th of May. The main objective of these rounds was to test the competitor's basis functionality. In total there were 70 simulated games. 40 in which the participant was alone competing with the default broker, and 30 with 8 players in the same game. Since there were 8 teams in the competition, this means that each broker participated in a grand total of 35 games during the Qualification Rounds.

  After the first 5 rounds, in which the broker was only facing the Default Broker, TugaTAC placed 4th, amongst 8 competitors, and was able to maintain a positive cash balance throughout the games as seen on table 4.1.

  After the last 30 rounds, in which the broker was competing with every other participant, TugaTAC dropped one place and ended in the 5th position with a negative balance (see figure 4.2). The results presented in the table are cumulative from the 30 rounds. During these rounds, a bug in the implementations was found, that was blocking the broker from participating in the Wholesale Market, making it lose plenty of money with balancing fees.

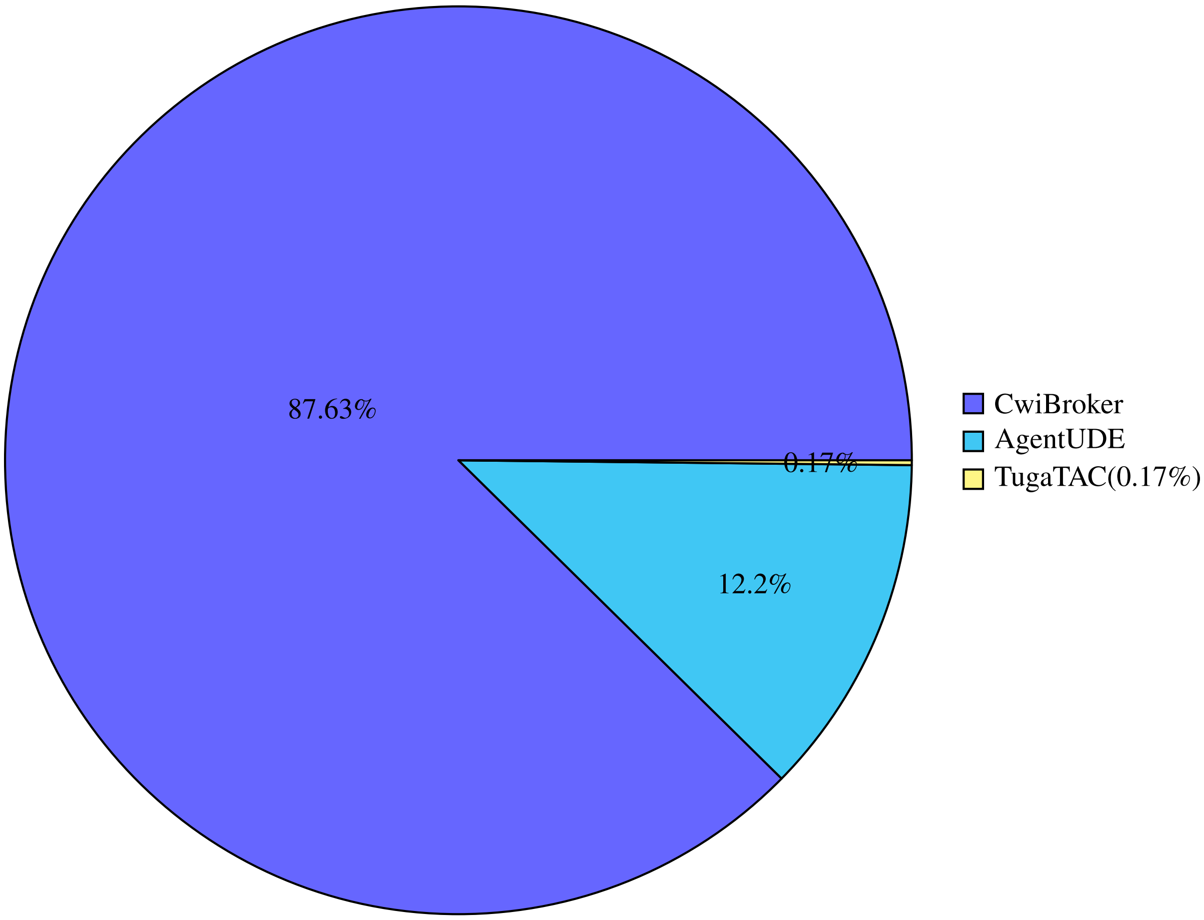

Figure 4.6: Market share distribution in a game agains CwiBroker and AgentUDE

Additionally, TugaTAC was also not able to consistently acquire as much market share as in previous experiences. In rounds were the market-share was almost reduced to zero, such as the one represented on figure 4.7, the cash balance of TugaTAC remains steady during the whole game. This happens because since the TugaTAC is not selling more energy than it is buying, it is not being charged the heavy balancing fees that are a factor in other rounds.

- **Seeding Rounds**

  The Seeding Rounds occurred between the 1st and the 15th of June. TugaTAC participated in the initial rounds, but since we were unable to properly patch the issues that emerged during the qualification rounds, the results were negative, and TugaTAC finished last in thise rounds. After about 30 rounds, we decided to withdraw the broker from the competition, as the outcome did not look promising. It is also noteworthy that some of the agents with very poor results in the Qualification Rounds had significantly better results during the Seeding rounds. This might mean that other teams might also have experienced serious issues during the first rounds, but were able to fix them.

- **Finals**

Table 4.1: Results after 5 Single Player Qualification Rounds

Broker	Cash Balance	Placement
AgentUDE	101 871 671	1st
AgentCU	98 344 446	2nd
maxon16	49 521 996	3rd
TugaTAC	32 940 989	4th
Mertacor	262 648 478	5th
CrocodileAgent	-49 293 162	6th
COLDPower	-53 359 217	7th
SPOT	-203 510 555	8th

Table 4.2: Results after 30 Multi Player Qualification Rounds

Broker	Cash Balance	Placement
AgentUDE	549 807 385 732 291 500 000 000 000 000 000 000 000 000 000	1st
COLDPower	111 014 612 465 068 960 000 000 000 000 000 000 000 000 000	2nd
SPOT	42 802 449 678 556 076 500 000 000 000 000 000	3rd
Mertacor	-55 396	4th
TugaTAC	-446 280 088 571 135 616	5th
maxon16	-311 171 110 437 594 000 000 000 000 000 000 000 000 000	6th
CrocodileAgent	-617 946 867 692 328 700 000 000 000 000 000 000 000 000 000	7th
AgentCU	-9 498 634 501 585 976 000 000 000 000 000 000 000 000 000 000	8th

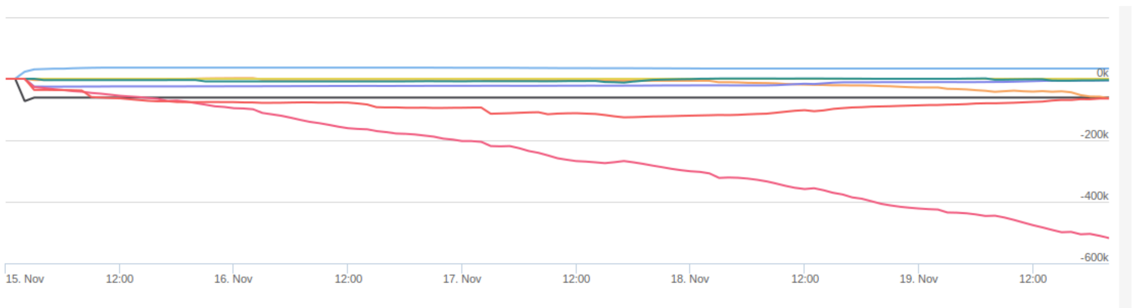

Figure 4.7: Profit chart for the Qualification Rounds (TugaTac is the Black Line)

The final rounds of the PowerTAC competition will occur between the 22nd of June and the 3rd of July. The participation requires the team to be registered for the TAC2016 competition, and that includes a hefty signup fee. Since we decided to withdraw from competition during the seeding rounds, TugaTAC also did not participate in the finals.

4.3 Analysis

4.3.1 Results

From the overall result of the experiments it seems that the narrow focus in the Tariff problem produced good results in the Retail Market. Additionally it can be said that it works better against the Default Broker, and against many competitors, as shown in the remote experiments. The broker often had the upper hand in market share and profit from that Market. However, the lack of an effective strategy for the Wholesale Market makes for a poor overall performance. This points toward the fact that the Wholesale Market has a much larger influence in the broker's finances than what was initially predicted.

As for an explanation for the cash losses that occurred in plenty of the experiences, since the broker's strategy for the Retail Market is to offer the most competitive strategy that is still profitable, generally it would end up with a large customer base. Since most of those customers are consumers, the energy they consume must be bought from somewhere. While the broker also gained most of the retail producers, in these simulations the ratio of producers/consumers in the retail market makes it so that there is not enough energy, and the brokers must resort to the wholesale market. Without a good strategy, the broker would either buy energy at a too high price, losing money in the trade, or not be able to buy energy at all, incurring in balancing fees. In the games with the largest losses, the Balancing Fees represented the largest chunk of cash transactions.

The Remote Experiments did not include results for the Default Broker, but it would be interesting to see how it would do against 8 opponents. Given what we saw in the local experiments, it is possible that the Default Broker would be better than many competitors with complex strategies.

In figure 4.7 we can see the balances for the brokers during the beginning of one of the qualification rounds. The pink line, represents the balance of AgentCU, that in just five simulated days managed to wildly break away from the norm, accumulating losses of over 500k. AgentCU is a new competitor, and no information has been made public about its functioning, so for now, the negative results cannot be attributed to any specific trait, but it comes to show that the current state of broker agent and strategy development and testing still has a long way to go.

4.3.2 Improvements

The obvious improvement to be made is to develop an effective strategy for the wholesale market. This strategy could simply be to buy the energy at market price, since like it was said previously, the Balancing Fees cause a much greater loss than a series of losing trades. This should be done in a way that takes advantage of the modular architecture of the broker.

The performance of the Decision Agent can be further increased by using Reinforcement Learning techniques in the selection process. Similarly, the techniques employed by the specialist agents still have a lot of room to improvement, as do the ones on the tariff manager agents.

Chapter 5

Conclusions and Future Work

This chapter contains a section with the main conclusions from the development of this dissertation, and another pointing in the direction of further development.

5.1 Conclusions

5.1.1 Contributions

The main contributions to knowledge on this work were the development of a MAS architecture and of a model for tariff selection, which meant improvements in the broker.

5.1.2 Results

Regarding the problems mentioned in the Introduction: how to create and manage efficient tariffs; how can be software agents be used ot improve tariff creation and how to explore the knowledge to produce different tariffs, the results were mostly positive. The developed strategy was in fact capable of creating, maintaining and selecting efficient Tariffs, with the use of software agents. The developed system is not very complex, nonetheless it shows that the use of software agents can bring several benefits. As for the knowledge exploration question, it was not given as much importance as was initially planned. This happened due to several reasons, the main one being the relatively low benefit it would seem to bring, considering the time expense in implementation and the low intricacy of the data to be analysed. As such, the knowledge exploration was done superficially, without the use of advanced techniques. However, the modular architecture used in the development makes it easier to perform more advanced knowledge exploration in the future taking a sectioned approach.

5.1.3 Hypothesis

With reference to the hypothesis placed in the beggining, the following was concluded:

- **Hypothesis 1**

Considering agents as specialists on subdomains (such as weather, supply and demand forecasts) that have complementary insights for the tariff, they can coordinate to create a final tariff.

This hypothesis is confirmed. The implemented system uses a group of specialist agents, and a group of manager agents, whose efforts are coordinated by the decision agent, proving the hypothesis to be true.

- **Hypothesis 2**

  Representing a Broker as a Multi-Agent System, we can enhance the performance of the tariff on the market, not only for the broker (profitability) but also for the customers (attractiveness).

  The second hypothesis is also valid. The broker achieved high profits and market shares up to 76% (see figure 4.3). Even though the results were not consistently high across all the games, we can say that the Multi-Agent representation is capable of producing better results.

5.2 Results and Analysis

5.2.1 Outline of the Solution

The result of the developed work was a functioning energy broker based on a Multi-Agent Architecture. The system is divided in 3 main components, the Specialist Layer, the Management Layer and the Decision Agent. The Specialist Layer is responsible for receiving information, analysing it and relaying relevant information to the Management. The Management uses the received info to compose Tariffs, that are then sent to the Decision Agent. The Decision Agent uses a decision model based on the evaluation of each Tariff, and then decides on which actions to take. The main focus of the system is the Retail Market, specifically the Tariff creation and maintenance problem.

5.2.1.1 Limitations

As was previously stated, the fairly narrow focus of the system on the Retail Market has made for a poor approach to the Wholesale Market, this being the largest limitation of the project. Besides that, the ability to perform extensive knowledge exploration was not included, but it did not seem to have a very serious impact on the performance. As such, the largest shortcoming of the broker is by far the unsatisfactory performance in the Wholesale Market, which annulled the successes in the retail market.

5.3 Future Work

This section contains the next steps that should be taken in order to improve the broker and its performance. The improvements listed have the goal of taking full advantage of the potential of the MAS architecture.

5.3.1 Wholesale Strategies

The development of better wholesale strategies is paramount to the development of an actually viable broker. Since this was the most significant point of failure, correcting it takes precedence over most other tasks. The developed strategies can be a strict correlating the amount of energy bought disregarding the price, or use other advanced techniques to predict how the market will evolve, and the consumption will change, but not much can be said about their effectiveness without actually the strategies actually being tested.

5.3.2 Improvements on the Specialists

Another important point of improvement is to further develop the Specialist Agents. One of the areas with more potential for improvement is tied to the knowledge exploration. The Specialist Agents already have at their disposal most of the information that can be gathered from the simulation server, and now the next step is to extract even more value from that information. This can be done similarly to what was attempted in the Weather Agent. It is possible, even likely, that other areas of knowledge can benefit more from advanced prediction techniques than the weather.

5.3.3 New Tariff Manager Models

After the improvements on the Specialist Agents provide an even greater source of knowledge to be used in the creation of tariffs, the next logical step is to improve the Tariff Manager Agents and Models to use that information as a path to performance increase. The increased variety in Tariff creation could potentially bring further improvements in the realization of the broker's goals.

Bibliography

[AW05] S Massoud Amin and Bruce F Wollenberg. "Toward a smart grid: power delivery for the 21st century". In: *IEEE power and energy magazine* 3.5 (2005), pp. 34–41.

[BP13] Jurica Babic and Vedran Podobnik. "An Analysis of Power TAC 2013 Trial." In: *AAAI Workshop: Trading Agent Design and Analysis*. 2013.

[BP14a] Jurica Babic and Vedran Podobnik. "Adaptive bidding for electricity wholesale markets in a smart grid". In: *AAMAS Workshop on Agent-Mediated Electronic Commerce and Trading Agents Design and Analysis (AMEC/TADA 2014)*. 2014.

[BP14b] Jurica Babic and Vedran Podobnik. "An analysis of power trading agent competition 2014". In: *Agent-Mediated Electronic Commerce. Designing Trading Strategies and Mechanisms for Electronic Markets*. Springer, 2014, pp. 1–15.

[BPR01] Fabio Bellifemine, Agostino Poggi, and Giovanni Rimassa. "Developing multi-agent systems with a FIPA-compliant agent framework". In: *Software-Practice and Experience* 31.2 (2001), pp. 103–128.

[BPR99] Fabio Bellifemine, Agostino Poggi, and Giovanni Rimassa. "JADE–A FIPA-compliant agent framework". In: *Proceedings of PAAM*. Vol. 99. 97-108. London. 1999, p. 33.

[CHL10] Meng Chang, Minghua He, and Xudong Luo. "Designing a successful adaptive agent for TAC Ad auction". In: (2010).

[Col03] Nick Collier. "Repast: An extensible framework for agent simulation". In: *The University of Chicago's Social Science Research* 36 (2003), pp. 371–375.

[Far10] Hassan Farhangi. "The path of the smart grid". In: *IEEE power and energy magazine* 8.1 (2010), pp. 18–28.

[Got+11] Sebastian Gottwalt et al. "Demand side management—A simulation of household behavior under variable prices". In: *Energy Policy* 39.12 (2011), pp. 8163–8174.

[Her+15] Pablo Hernandez-Leal et al. "Bidding in Non-Stationary Energy Markets". In: *Proceedings of the 2015 International Conference on Autonomous Agents and Multiagent Systems*. International Foundation for Autonomous Agents and Multiagent Systems. 2015, pp. 1709–1710.

[Hoo14] Jasper Hoogland. "Power TAC cwiBroker2014". In: (2014).

[Jac09] Matthew O Jackson. “Networks and economic behavior”. In: *Annu. Rev. Econ.* 1.1 (2009), pp. 489–511.

[Jos+08] Paul L Joskow et al. *Lessons Learned from the Electricity Market Liberalization*. Massachusetts Institute of Technology, Center for Energy and Environmental Policy Research, 2008.

[JW96] Nicholas R Jennings and Michael J Wooldridge. “Software agents”. In: *IEE review* (1996), pp. 17–20.

[KCB10] Wolfgang Ketter, John Collins, and Carsten A Block. “Smart grid economics: Policy guidance through competitive simulation”. In: (2010).

[KCR13] Wolfgang Ketter, John Collins, and Prashant Reddy. “Power TAC: A competitive economic simulation of the smart grid”. In: *Energy Economics* 39 (2013), pp. 262–270.

[KCW14] Rodrigue T Kuate, Maria Chli, and Hai H Wang. “Optimising Market Share and Profit Margin: SMDP-based tariff pricing under the smart grid paradigm”. In: *Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES*. IEEE. 2014, pp. 1–6.

[KCW16] Wolfgang Ketter, John Collins, and Mathijs De Weerdt. “The 2016 Power Trading Agent Competition”. In: *ERIM Report Series Reference* (2016).

[Ket+11] Wolfgang Ketter et al. “The power trading agent competition”. In: *ERIM Report Series Reference No. ERS-2011-027-LIS* (2011).

[Ket+12] Wolfgang Ketter et al. “Real-time tactical and strategic sales management for intelligent agents guided by economic regimes”. In: *Information Systems Research* 23.4 (2012), pp. 1263–1283.

[KPC13] Wolfgang Ketter, Markus Peters, and John Collins. “Autonomous agents in future energy markets: the 2012 power trading agent competition”. In: *BNAIC 2013: Proceedings of the 25th Benelux Conference on Artificial Intelligence, Delft, The Netherlands, November 7-8, 2013*. Delft University of Technology (TU Delft); under the auspices of the Benelux Association for Artificial Intelligence (BNVKI), the Dutch Research School for Information, and Knowledge Systems (SIKS). 2013.

[KS12] Wolfgang Ketter and Andreas Symeonidis. “Competitive benchmarking: Lessons learned from the trading agent competition”. In: *AI Magazine* 33.2 (2012), p. 103.

[LHL14] Bart Liefers, Jasper Hoogland, and Han La Poutré. “A successful broker agent for power tac”. In: *Agent-Mediated Electronic Commerce. Designing Trading Strategies and Mechanisms for Electronic Markets*. Springer, 2014, pp. 99–113.

[Mat+12] Sinisa Matetic et al. “The CrocodileAgent 2012: Negotiating Agreements in Smart Grid Tariff Market.” In: *AT*. 2012, pp. 203–204.

[NCM14] Eleni Ntagka, Antonios Chrysopoulos, and Pericles A Mitkas. "Designing tariffs in a competitive energy market using particle swarm optimization techniques". In: *Agent-Mediated Electronic Commerce. Designing Trading Strategies and Mechanisms for Electronic Markets*. Springer, 2014, pp. 129–143.

[NPM12] Vilém Novák, Irina Perfilieva, and Jiri Mockor. *Mathematical principles of fuzzy logic*. Vol. 517. Springer Science & Business Media, 2012.

[ON98] Patrick D O'Brien and Richard C Nicol. "FIPA—towards a standard for software agents". In: *BT Technology Journal* 16.3 (1998), pp. 51–59.

[ÖU15] Serkan Özdemir and Rainer Unland. "The Broker Strategies of a Winner Agent in Power TAC". In: (2015).

[Pet+12] Markus Peters et al. "Autonomous data-driven decision-making in smart electricity markets". In: *Joint European Conference on Machine Learning and Knowledge Discovery in Databases*. Springer. 2012, pp. 132–147.

[Pro13] DT Prosch. *Trading Agents in the 2013 Power TAC Competition*. Erasmus Universiteit, 2013.

[R+95] Anand S Rao, Michael P Georgeff, et al. "BDI agents: From theory to practice." In: *ICMAS*. Vol. 95. 1995, pp. 312–319.

[RQ15] Thiago R.P.M. Rúbio and Jonas Queiroz. "TugaTAC Broker: A Fuzzy Logic Adaptive Reasoning Agent for Trading Energy". In: (2015).

[RV13] Prashant P Reddy and Manuela M Veloso. "Negotiated learning for smart grid agents: entity selection based on dynamic partially observable features". In: AAAI. 2013.

[SZ11] Victor Stango and Jonathan Zinman. "Fuzzy math, disclosure regulation, and market outcomes: Evidence from truth-in-lending reform". In: *Review of Financial Studies* 24.2 (2011), pp. 506–534.

[Tal+13] Rodrigue Talla Kuate et al. "An intelligent broker agent for energy trading: An mdp approach". In: AAAI. 2013.

[TKM06] Panos Toulis, Dionisis Kehagias, and Pericles A Mitkas. "Mertacor: a successful autonomous trading agent". In: *Proceedings of the fifth international joint conference on Autonomous agents and multiagent systems*. ACM. 2006, pp. 1191–1198.

[TW04] Seth Tisue and Uri Wilensky. "Netlogo: A simple environment for modeling complexity". In: *International conference on complex systems*. Vol. 21. Boston, MA. 2004.

[Tyk10] Dmytro Tykhonov. *Designing generic and efficient negotiation strategies*. TU Delft, Delft University of Technology, 2010.

[US14] Daniel Urieli and Peter Stone. "Tactex'13: a champion adaptive power trading agent". In: *Proceedings of the 2014 international conference on Autonomous agents and multi-agent systems*. International Foundation for Autonomous Agents and Multiagent Systems. 2014, pp. 1447–1448.

[Woo97] Michael Wooldridge. "Agent-based software engineering". In: *Software Engineering. IEE Proceedings-[see also Software, IEE Proceedings]*. Vol. 144. 1. IET. 1997, pp. 26–37.