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A Multi-Agent System Simulation Model for Trusted Local Energy Markets

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Dedicatory

To my family and friends who encourage to go further

Abstract

The energy market and electric grid play a major role in everyday life. Most areas in modern society, such as: communication, health, transportation, the financial system and many others; require electrical energy to operate properly. Traditionally energy grids operate in a centralized manner. Consumers are connected to centralized utilities in the grid and energy flows from producers to Consumers. However, the rising in popularity in Renewable Energy Sources (RES) such as photovoltaic panels installed in households, small commerce and small industry wide spread the use of distributed energy generation, which the main energy grid was not designed to support.

One of the possible solutions for this problem is the creation of a Local Energy Market (LeM). A LeM is a market that operates in a small physical area such as a neighborhood. Traditional consumers can become active market participants under a LeM. That is possible because the LeM is structured in such a way as to enable small-scale negotiations and energy exchanges between participants, who traditionally would only be final consumers. The LeM is capable of dealing with distributed energy generation from RES because negotiations and distribution happen at a local level, thus reducing problems with the main grid. Furthermore, the participation in the local market can reduce energy costs or even create profits for consumers, while contributing to easy the management of the grid and associated technical losses.

This work explores the concept of LeM and is focused on two main objectives: designing and developing a system that allows the simulation of LeM, and designing and developing a mechanism that allows trusted negotiations in this market. To accomplish these objectives a Multi-Agent System (MAS) architecture is proposed to model and allow the simulation of LeM. Furthermore to support the market it is also proposed a trust model used to evaluate the behavior of participants and detecting faulty or malicious activities.

The developed MAS models a LeM based on a Smart Grid, that is an energy grid with a cyber-physical system with smart meters and communications mechanisms. The MAS was developed with agents to model sensors, market participants and a Market Interaction Manager (MIM) agent that is responsible for managing the negotiations and for applying trust mechanisms. The trust mechanism was designed to attribute a dynamic trust value to each participant, which is reviewed during the all negotiation period. This evaluation of the participant's trust is based on the analysis of historical data, contextual data, such as weather conditions, and by using forecasting methods to predict the participant expected behavior, allowing to penalize the ones that are exhibiting a questionable behavior in the market.

A case study simulation was made with the objective of understanding how the proposed trust mechanism performed, and how the use of different forecasting methods can interfere with it. The results obtained allowed us to conclude that the trust methodology is able to update the trust of each participant, during the negotiation period, and when paired with

a well performing forecasting mechanism it is able to achieve a trusted evaluation of the participants behavior.

Taking into consideration these results we believe that the proposed trust methodology is capable of providing a valuable trust assessment when used by the MIM agent.

This Master Thesis is developed within the scope of a project called Secure interactions and trusted Participation in local Electricity Trading (SPET), a FCT-SAICT2017 funded Research & Development project. SPET project envisions the development of a MAS that is designed to model and simulate the operations of a LeM, taking a focus on security and market trust necessary in this negotiation environment.

Keywords: Local Energy Markets, Multi-Agent Systems, Trust

Resumo

O mercado de energia e a rede elétrica desempenham um papel importante na vida quotidiana da população. Grande parte das áreas da sociedade moderna, como é o caso da comunicação, transportes, saúde, sistema financeiro, entre outras; requer energia elétrica para funcionar corretamente. Tradicionalmente, as redes de energia operam de forma centralizada. Os consumidores estão conectados às fornecedores centralizados na rede e a energia é transferida dos produtores para os consumidores. No entanto, o aumento da popularidade das Fontes de Energia Renováveis (FER), como painéis fotovoltaicos instalados nas residências, pequeno comércio e pequena indústria, difundiu o uso da geração distribuída de energia, que a rede principal de energia não foi projetada para suportar.

Uma das possíveis soluções para esse problema é a criação de um Mercado Local de Energia (MLe). Um MLe é um mercado que opera numa pequena área física, como uma vizinhança. Num MLe, os consumidores tradicionais têm a possibilidade de ser participantes ativos no mercado.

Isto é possível porque o MLe está estruturado de forma a permitir negociações em pequena escala e trocas de energia entre os participantes, que tradicionalmente seriam apenas consumidores finais. O MLe é capaz de lidar com a geração de energia distribuída proveniente das FER, porque as negociações e a distribuição ocorrem a um nível local, reduzindo assim os problemas com a rede principal. Para além disso, a participação no mercado local pode reduzir os custos de energia ou até gerar lucros para os consumidores, contribuindo ainda para facilitar a gestão da rede e reduzir as perdas técnicas a ela associadas.

Este trabalho explora o conceito de MLe e está focado em dois objetivos principais: projetar e desenvolver um sistema que permita a simulação de MLe, bem como um mecanismo que permita negociações confiáveis neste mercado. Para atingir estes objetivos, é proposta uma arquitetura de Sistema Multi-Agente (SMA) para modelar e permitir a simulação do MLe. Para além disso, para apoiar o mercado, também é proposto um modelo de confiança utilizado para avaliar o comportamento dos participantes e detetar falhas ou atividades maliciosas.

O SMA desenvolvido modela um MLe com base numa Smart Grid, que é uma rede de energia com um sistema ciber-físico, com sensores inteligentes e mecanismos de comunicação. O SMA foi desenvolvido com agentes para modelar sensores, participantes do mercado e um agente Market Interaction Manager (MIM), responsável pela gestão das negociações e pela aplicação de mecanismos de confiança. O mecanismo de confiança foi projetado para atribuir um valor de confiança dinâmico a cada participante, que é adaptado durante todo o período de negociação. Essa avaliação da confiança do participante é baseada na análise de dados históricos, contextuais, como condições climatéricas, e no uso de métodos de previsão para antever o comportamento esperado do participante, permitindo penalizar aqueles que exibem um comportamento questionável no mercado.

Foi realizada uma simulação de caso de estudo, com o objetivo de avaliar o desempenho do mecanismo de confiança proposto e de que forma é que o uso de diferentes métodos

de previsão interfere neste desempenho. Os resultados obtidos permitiram concluir que a metodologia de confiança é capaz de atualizar a confiança de cada participante, durante o período de negociação e, quando combinada com um mecanismo de previsão com bom desempenho, é capaz de obter uma avaliação confiável do comportamento dos participantes.

Tendo em consideração estes resultados, acreditamos que a metodologia de confiança proposta é capaz de fornecer uma avaliação de confiança valiosa quando usada pelo agente MIM.

Esta tese de mestrado é desenvolvida no âmbito de um projeto chamado Secure interactions and trusted Participation in local Electricity Trading (SPET), um projeto de Investigação e Desenvolvimento (I&D) financiado pela FCT-SAICT2017. O projeto SPET tem como objetivo o desenvolvimento de um MAS para a modelação e simulação de MLe, tendo como foco a segurança e confiança necessárias neste ambiente de negociação.

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Rui Andrade

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List of Symbols

ar	acceptance range
tiv	trust increase value
tdv	trust decrease value
sv_{pi}	submitted value participant p in negotiation period i
fv_{pi}	forecasted value for participant p in negotiation period i
t_{p0}	default trust value
t_{pi}	trust value for a participant p in negotiation period i
h_t	minimum threshold for high trust
m_t	minimum threshold for medium trust
$\bar{x}$	mean
σ	standard deviation

List of Acronyms

ACL	Agent Communication Language.
AMES	Agent-based Modelling of Electricity Systems.
ANN	Artificial Neural Network.
ARIMA	Autoregressive Integrated Moving Average.
BDI	Belief Desire Intention.
DemCos	Demand Companies.
DER	Distributed Renewable Energy Resources.
DistCos	Distribution Companies.
DoS	Denial of Service.
DSO	Distribution System Operators.
EMCAS	Electricity Markets Complex Adaptive System.
Exp3	Exponential-weight algorithm for Exploration and Exploitation.
FERC	U.S. Federal Energy Regulatory Commission.
FRBS	Fuzzy Rule Base System.
GAPEX	Genoa Artificial Power Exchange.
GenCos	Generation Companies.
GNP	Gross National Product.
HyFIS	Hybrid Neural Fuzzy Inference System.
IEEE	Institute of Electrical and Electrotechnical Engineering.
ISOs	Independent System Operators.
JADE	Java Agent DEvelopment Framework.
JSON	JavaScript Object Notation.
LeM	Local Energy Market.
LGC	Local Grid Controller.
LSEs	Load-Serving Entities.
LV	Low Voltage.
MAS	Multi-Agent System.
MASCEM	Multi-Agent Simulator of Competitive Electricity Markets.

MDP	Markov Decision Process.
MIM	Market Interaction Manager.
MPC	Secure Multiparty Computation.
MV	Medium Voltage.
ODB	Outcomes Data Base.
ORM	Object-Relational Mapping.
PoCC	Point of Common Coupling.
R&D	Research & Development.
REM	Retail Electricity Market.
RES	Renewable Energy Sources.
SARIMA	Seasonal Autoregressive Integrated Moving Average.
SESP	Smart Energy Service Provider.
SPET	Secure interactions and trusted Participation in local Electricity Trading.
SQL	Structured Query Language.
SVM	Support Vector Machine.
TransCos	Transmission Companies.
TRS	Trust and Reputation Systems.
TSO	Transmission System Operator.
UCB1	Upper Confidence Bound.
VPP	Virtual Power Player.
WEM	Wholesale Electricity Market.
XML	Extensible Markup Language.

Chapter 1

Introduction

This chapter intends to give an overall description of the theme addressed in this dissertation, that is, the proposal and development of a simulation system for local energy trading that considers the aspects of security in the network and trust among the Local Energy Market (LeM) participants. The theme is presented in Section 1.1, then Section 1.2 exposes the objectives of this work. Finally, Section 1.3 presents the document structure.

1.1 Context

The energy market and electric grid play a major role in everyday life. Most areas in modern society, such as: communication, health, transportation, the financial system and many others; require electric energy to operate properly. The electric grid has become such an ubiquitous utility, and modern societies have become so dependent on it that it would be hard to imagine what could happen without it. These reasons are self-evident when it comes to showing that maintaining and improving the stability and reliability of the energy grid can play a major role in the progress of humanity.

Currently energy grids tend to follow a very strict and somewhat inefficient structure. A high number of entities, that desire to consume energy, are connected to a single centralized energy supplier entity. Traditional energy markers, such as wholesale or retail markets, were not designed to support the rising of distributed energy generation coming from Renewable Energy Sources (RES) in households, small commerce and small industry. Such facts raise questions about different ways of structuring energy markets to deal with these challenges.

One of the possible proposals to answer to this problem is the creation and implementation of LeM. LeM are structured in such a way as to enable small-scale negotiations and energy exchanges between participants, who traditionally would only be final consumers. These markets are designed to operate within a regional area, such as a neighborhood or a city. Participants in this market are the local households, small commerce and small industry, that may be regular consumers or consumers with some type of local energy generation, being referred to as prosumers. Furthermore, local small-scale power plants can also participate in the LeM. The LeM is better designed to deal with distributed energy generation from RES because the surplus in generation from local energy producers and prosumers can be purchased and utilized by local consumers. This flexibility of response makes LeM an attractive proposition for the future of energy markets.

This Master Thesis is developed within the scope of a project called Secure interactions and trusted Participation in local Electricity Trading (SPET), an FCT-SAICT2017 funded Research & Development (R&D) project. SPET project envisions the development of a

Multi-Agent System (MAS) that is designed to model and simulate the operations of a LeM.

A MAS is a system that combines several Agents, these are software entities that have the capacity to interact among themselves. The concept of Agent is quite simple, it is an entity that can sense its world and environment and preform actions in said environment, accordingly to its intentions. Within the context of Power and Energy systems, a single Agent can perform a simple task, such as deciding whether or not to make a bid in the LeM. However, several Agents working together in a MAS can respond to far more complex problems. A MAS can be a response for some of the needs faced in the implementation of a LeM. Local market participants can be represented by Agents that carry out the necessary management and negotiation operations.

1.2 Objectives

Within the scope of SPET project it is intended to create a tool capable of meeting the security and trust needs that are relevant to electricity trading, in LeM. A market simulation tool is developed in which communication mechanisms need to ensure security for the participants and integrate trust mechanisms that can infer trust in market participation. Participants that alter their information or, in some other way, try to gain some undeserved advantage in the LeM, such as receiving a monetary payment without supplying the energy load agreed in a negotiation, should be identified with a low level of trust. To better delineate the objectives in this thesis some focus points are presented:

- Develop a simulation environment based on a MAS to study LeM;
- Allow negotiations between participants in the LeM;
- Incorporate trust mechanisms in the LeM;
- Apply a trust model to score participants trust level during negotiations.

1.3 Document Structure

After this introductory section, this document is organized as follows: Chapter 2 presents the context of the work, describing energy markets and further detailing the concepts of the LeM, of MAS, and of trust models for MAS. Chapter 3 describes the proposed solution and its development. Chapter 4 delineates how the experimentation and evaluation process was be performed. Lastly, Chapter 5 presents the conclusions of this work.

Chapter 2

Context

This thesis is developed as part of an FCT-SAICT2017 funded Research & Development (R&D) project called Secure interactions and trusted Participation in local Electricity Trading (SPET) that aims towards taking advantage of the spread of Renewable Energy Sources (RES) and smart meters in households. These technologies, and demand flexibility in local communities, open the possibility for the development of a Local Energy Market (LeM), where consumers, producers and prosumers can participate, trading energy locally and in a more ecological way due to the emphasis on RES. The LeM needs to provide mechanisms to accurately define the needs of participates, maintain the security in the system and ensuring the trust in the negotiations. The vision of SPET project is to develop a Multi-Agent System (MAS) capable of simulating LeMs, including a Market Interaction Manager (MIM) agent that will oversee and ensure trustful participation.

This Chapter introduces the context of this dissertation. Section 2.1 describes energy markets in broad terms. Section 2.2 details LeM and presents the work and proposals of several authors. Section 2.3 presents forecasting methods applied in energy contexts. Section 2.4 details the security and trust concerns present in LeM. Section 2.5 describes the concept of a MAS. Section 2.6 details development platforms for MAS. Section 2.7 presents MAS developed in the context of energy markets. Section 2.8 describes trust mechanisms for MAS. And finally, Section 2.9 presents an overview of the chapter.

2.1 Energy Markets

Energy markets can operate and be structured in a variety of different ways. Several entities work together to form these markets and negotiate distinct types of contracts depending on their needs and context. The following settings address these topics.

2.1.1 Entities in Energy Markets

Energy Markets are composed of a vast number of distinct entities and groups of entities that together create the ecosystems necessary for the energy markets. Understanding these entities and the role they play in the market is an important step towards achieving a solid and global understanding of Energy Markets. The following is a list of common and relevant entities in energy markets:

- **Consumer**: Consumer is the name given to any market player that wishes to consume energy Rosen and Madlener 2016;
- **Producer**: Producer is the term applied to energy producers, such as larger generation stations, that wish to sell the energy they produce Rosen and Madlener 2016;

- **Prosumer**: Prosumer is a more recent term that is the result of the terms "consumer" and "producer" combined. This combination is to represent an end consumer such as a household or a small industry that also have their own energy generation mechanisms Rosen and Madlener 2016;
- **Renewable Energy Sources**: Renewable Energy Sources (RES) refers to energy sources that can be sustainable and will not have a finite supply such as fossil energy sources. Photovoltaic panels and wind turbines are the most common in the context of prosumer households Carrasco et al. 2006;
- **Smart Grid**: A Smart Grid is an energy grid capable of preforming the autonomous intelligent management of its own energy generation and consumption demands in an efficient way. The basis for the Smart Grid are the smart meters that collect context aware data on the energy consumption and generation, and the communications mechanisms that allow the entities in the grid to work together in order to efficiently meet the needs of all participants Amin 2015;
- **Micro Market**: A Micro Market is the term used to describe an energy market that is built on the bases of a micro grid. Such a market operates on a small area, has a high density and number of participants, but operates with transactions of small quantities of energy Cox and Considine 2011;
- **Virtual Power Player**: A Virtual Power Player (VPP) is an entity that represents the combination of smaller energy generation devices working together in order to operate as a large power plant. With this aggregation approach, the VPP is able to participate in markets targeted at large players Rosen and Madlener 2016;
- **Transmission System Operator**: Transmission System Operator (TSO) refers to a legal entity responsible for operating and managing the infrastructure used for the transport of high voltage electricity Głowack n.d. TSO operate at the level of transporting electricity to large players such as power plants;
- **Distribution System Operator**: In contrast with the TSO the Distribution System Operators (DSO) refers to a legal entity responsible for operating and managing the infrastructure used for the distribution of medium and low voltage electricity EDSO n.d. TSO operate at the level of transmission electricity to small players such as households, small commerce and small industry.

2.1.2 Energy Contracts

An Energy market, in its most simple description, is a market where participants can sell and buy energy. Currently these markets operate at two distinct levels, the retail market and the wholesale market. The retail market is the market that operates at the consumer level, selling the energy directly to the consumers. The retail market trades tend to be done by a fixed price contract and do not take into consideration the fluctuations in energy generation and demand Morey 2001. Such contracts, where the buyer trades directly with the seller are often called bilateral markers. By contrast, the wholesale market operates at the level of large energy players who must deal with high fluctuations in energy generation and demand and make their transactions through an intermediary. Markets that operate in this manner are called mediated markets.

In Bilateral Markets trades are set for the long time and the price is specific to each trade. These characteristics of long-term stable prices are specifically beneficial for individual consumers. In Mediated Markets the design of it is such that a unique Market Clearing price is set according to the supply and demand curves in the market as shown by Figure 2.1. The Market Clearing price is the price that will be set in the market to all participants. This price, and the auction itself, are performed at regular intervals in order to keep up with the market needs.

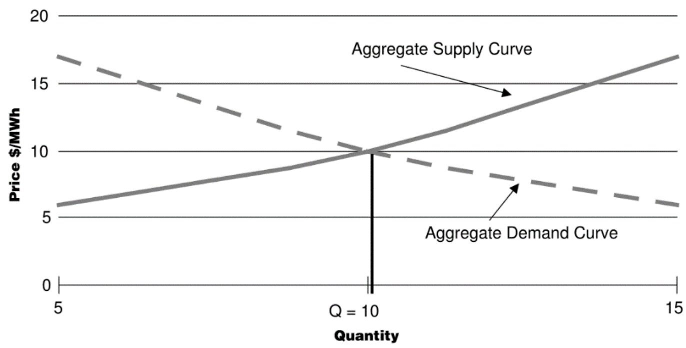

Figure 2.1: Market Clearing Price
Morey 2001

2.2 Local Energy Markets

The traditional energy markets operate in a centralized manner in relation to final consumers. Households, small commerce and small industry in the same local region are served by centralized energy providers, as schematized in Figure 2.2. However, the increase in RES in households, commerce and small industry are creating new demands in the energy grid De Vries, Verzijlbergh, et al. 2018.

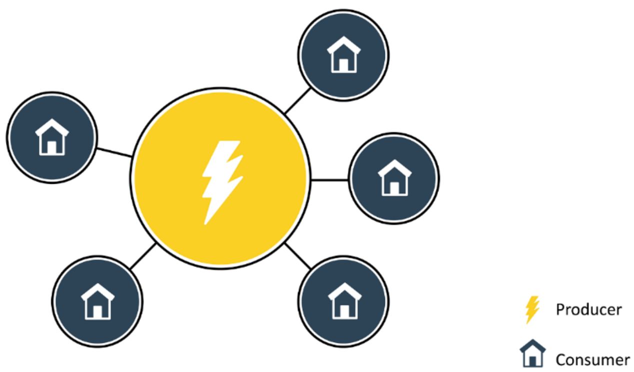

Figure 2.2: Centralized Market

RES generation is very unpredictable, and the energy grid needs to be prepared to deal with this fluctuation in generation grid De Vries, Verzijlbergh, et al. 2018. One real example where the LeM could be beneficial is Denmark to deal fluctuation in energy generation originated by RES Hvelplund 2006. The wind turbines in Denmark created such oscillation in generation that when the energy surplus is too high the only solution is to sell that energy, even if that comes at a loss. With a LeM energy can be traded locally, that means that excess energy generated locally by RES can be sold to local neighbors that cannot met their energy needs through self-generation nor are able to negotiate in wholesale markets. Such a market is structured with consumers and prosumers, as schematized in Figure 2.3. The LeM participants only interact with the centralized energy distribution grid when their needs cannot be guaranteed in the LeM.

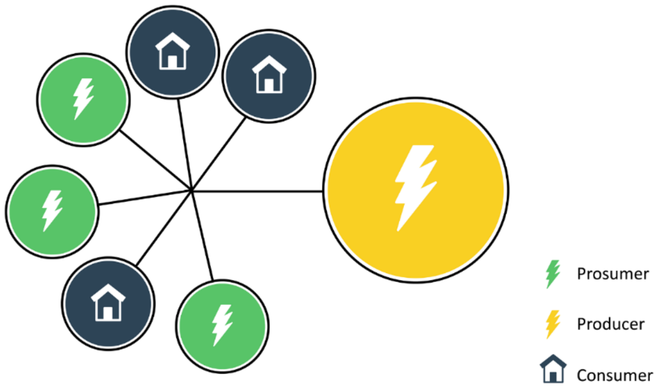

Figure 2.3: Distributed Market

The demands for LeM have made then a common field of study. Several authors have studied and proposed models for LeM. Analyzing and understanding these models is a crucial part in this thesis.

2.2.1 Approach by Abidin et al.

Abidin et al. 2016 propose the idea of a LeM as a market where the excess of electrical energy can be traded between the local market participants. This idea rests on top of a Smart Grid. The participants in this market are defined as households that have smart energy meters capable of reporting information to the Smart Grid and have their own energy generation with RES such as solar panels and wind turbines. The LeM proposed by Abidin et al. 2016 is illustrated in Figure 2.4.

The authors identify that such a market would have four advantages compared to those currently in operation:

- It would reduce the greenhouse gas emissions;
- It would make use of electricity lines more effectively;
- It would reduce costs;
- And it would increase profits for the user.

This work also makes some considerations towards the safety and privacy requirements that a system like this would require by identifying four threats that such a system would need to deal with. These threats are:

- Malicious users - tampers with data to gain financial advantage;

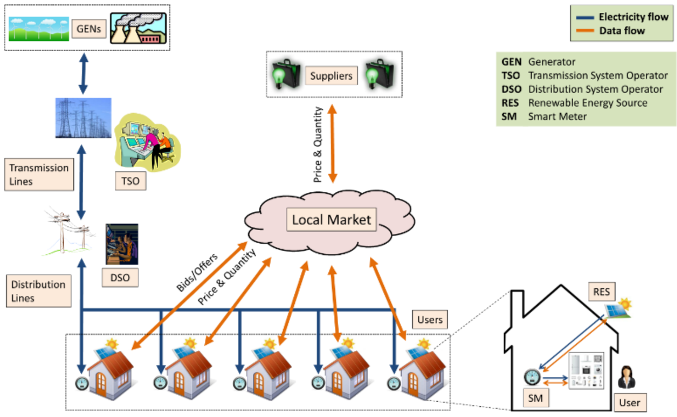

Figure 2.4: Local Energy Market design
Abidin et al. 2016

- Malicious suppliers - tampers with data to gain financial advantage;
- Unauthorized information gathering from participants;
- Unauthorized information gathering from external parties.

Their proposal makes use of public/private key to secure communications and Secure Multi-party Computation (MPC) Pullonen and Siim 2015, which is a protocol that allows adversarial entities to perform computational operations together and achieve correct results while making sure that each party only knows their secret inputs and outputs, and cannot infer any other information. The proposed market operates by allowing users to place offers or bids in the market, following a double auction trading scheme. The market them calculates an accepted clearing price and offers/bids that are matched within the accepted clearing price are the ones allowed to be performed. Energy requirements that are left unmatched are assured by the main energy grid. As a fail-safe, users that make an offer and are not able to fulfill it must take the responsibility of buying energy, from the main grid, to supply the buyer with the agreed energy amount.

2.2.2 EMPOWER Project

EMPOWER Bremdal, Olivella, and Rajasekharan 2017 is a research project, with funding from the European Commission through the H2020 program, aimed towards building a network based local market for energy trading. The EMPOWER project identifies several reasons that express the necessity for, and advantages of, LeMs. These reasons being:

- The increase, and improvement, in Smart Grid technologies and in Distributed Renewable Energy Resources (DER);
- The increased demand in clean energy due to the green shift and environmental concerns;
- The retail and wholesale market are currently not suited to face the challenges in the energy market;
- Consumers are more receptive to technological solutions that better serve their needs.

In this project the LeM is defined by its geographical locations, specifically a residential area and by being based on a Micro-Market. The physical energy distribution grid plays a major role in the definition of the local market, because all participants must be connected to a Point of Common Coupling (PoCC), the author identify a secondary substation as a PoCC. In EMPOWER project LeM participants are consumers, that may or may not possess energy generation, and storage facilities, furthermore their energy requirement revolve around Medium Voltage (MV) and Low Voltage (LV) loads. Their local market operates with an entity called Smart Energy Service Provider (SESP). The SESP is then responsible for managing the trades in the local market, with continuous double auctions. The authors view also support for bilateral contracts as beneficial. Additionally, SESP can behave as an aggregator, that is then able to negotiate as a single player with other local markets or even participate in the wholesale market. These operations may require coordination with the DSO and TSO. The authors also present some considerations regarding the aspects that can contribute to the success of the Local Markets:

- Profits from participating in the local market should be greater than from the central market;
- Sales in the local market should be more appealing than selling through an aggregator;
- The local market should incentivize participation, with simpler trades, when the local market is still establishing itself.

The EMPOWER project has managed to install a prototype LeM in Hvaler, Norway. The local community in that market grew quickly. Several energy suppliers and retailers have shown interest in the LeM opportunity. Photovoltaic energy generation increased in the region, and consumers are taking a more active place in the energy market. The authors say that it is too early to take any conclusions, but these early results are promising.

2.2.3 Approach by Teotia and Bhakar

Teotia and Bhakar 2016 presents an analysis of challenges in traditional energy markets and discusses the concept, design and operation of LeM. Traditional energy markets are presented as being one of two types: Wholesale Electricity Market (WEM) or Retail Electricity Market (REM). In Teotia and Bhakar 2016 point of view the WEM presents the following problems:

- Final consumers such as homes, small commerce and small industry do not have an active role in the decisions that influence the market, and do not take benefits from price drops in the wholesale market;
- Transmission lines are often a bottleneck in the market which may lead to increase in prices and inefficiency of the market;
- Operations of expansion of the transmission line may not be agreed by all stakeholders, thus perpetuating these transmission bottleneck problems;
- WEM operate in such a way that prevents small generation units to easily enter and participate in the market, which limits the competition in the market;
- Finally, the design of WEM did not take RES and variable generation into consideration. The increase in RES creates imbalances among players in the WEM. RES can bring increased risks in day-ahead and real-time prices due to the variability in generation. This may lead to increased costs due to the need for backup generation systems.

As for the REM, Teotia and Bhakar 2016 describe it as going throw the a process of change. The problems that lead this need of change are the following:

- Current REM take small attention to the interests of small commerce, small industry and households, only offering fixed electricity price tariffs and thus not giving consumers the possibility to benefit from price drops in the wholesale markets;
- The process for consumers to change their energy supplier is complicated and can have financial cost for the consumer. These barriers limit consumer participation and create a less competitive market;
- Rural areas tend to be left poorly served by REM. The necessary infrastructure investment by REM to support these areas is high and that leaves rural consumers with higher electricity prices;
- Currently no collaboration is made by REM and consumers to consider the possibility of shifting consumer energy loads in times of peak demand to times of less demand;
- Finally, the energy bill of the final consumer is inflated due to the need to support the variable cost of the WEM, investments in RES by retailers and power transmission costs.

In the face of these problems the authors present LeM as a solution by combining the generation, storage and demand response. The LeM proposed by Teotia and Bhakar 2016 consists in a local grid that incorporates local energy generation sources, local storage units and energy loads. Both consumers and prosumers are viewed as active participants in the LeM and shall use network communication technologies. The proposed LeM considers five key aspects in its design:

1. **Ownership**: A market based on local ownership can take a focus towards cost reducing and improving environmental sustainability from the point of view of the consumers;
2. **Delivery Mechanism**: The delivery mechanisms in the LeM are dependent on the type of electric current (AC/DC) and quantities produced;
3. **Community Link**: The LeM diminishes the consumer dependence on traditional energy markets to supply its needs and gives an active role to consumers that gain a financial interest in consuming energy efficiently;
4. **Size**: The size of the LeM can be variable in order to better accommodate the needs of participants;
5. **Structure of the LeM**: The LeM is structured as a component that can be incorporated with traditional energy markets, and coexisting in the same distribution grid as REM. The LeM can take an approach centered in stability and flexibility in response towards energy demands, and economical benefit with monitoring and energy trading.

In the proposed market design the local participants are connected to a Local Grid Controller (LGC) and make energy proposals as a bidding house. The LGC is responsible for managing participant interactions and energy demands within the local grid and interact with an aggregator that enables energy transferring among LeMs. Furthermore, LGC takes responsibility of the management tasks such as billing, data storage of decision-making. This LeM design is represented in Figure 2.5.

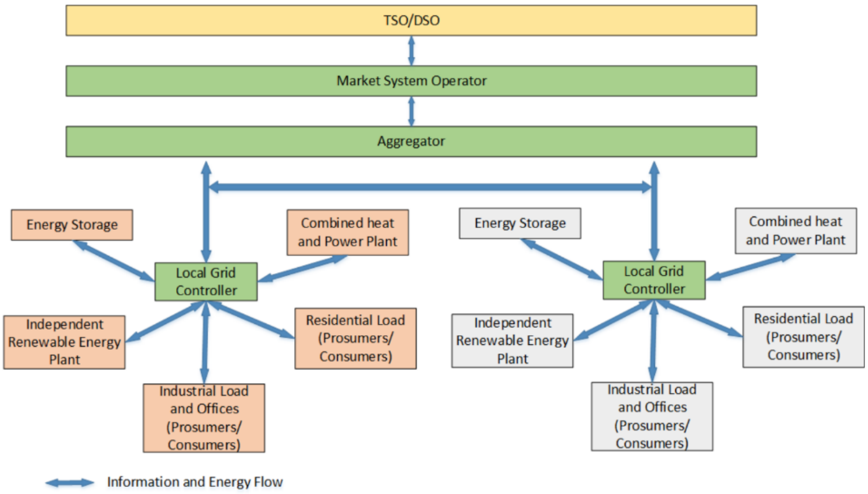

Figure 2.5: LeM design proposed by
Teotia and Bhakar 2016

2.2.4 DOMINOES Project

DOMINOES Mendes et al. 2018 is a research project, with funding from the European Commission through the H2020 program. In this work the authors explore the potential benefits that LeM can bring and also the current barriers preventing their adoption. Currently the project is envisioning a simple architecture for the LeM that encompass the exchange of energy between consumers, prosumers, DSO, aggregations, retailers, and other participant entities. This design in presented in Figure 2.6.

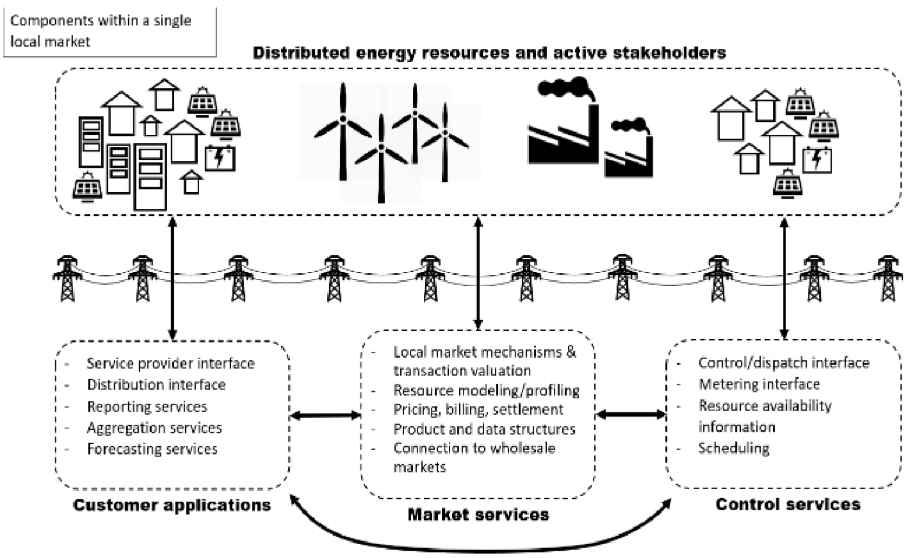

Figure 2.6: DOMINOES Project LeM concept
Mendes et al. 2018

The authors identify LeM as having benefits in four different levels as:

- **Customer**: Under a LeM customers can have RES and thus become prosumers. This helps them to reduce costs and may even bring profits;

- **Network operator**: The flexibility gained with the LeM bring benefits for the network operator because it reduces the need for investments in the distribution grid;
- **Service, technology and energy provider**: LeM bring new service opportunities, such as third-party entities that negotiate on the behalf of the consumer;
- **Society**: LeM can provide benefits for the society because they incentivize RES and sustainability.

The authors also identify four barriers faced by LeM:

- **Technical**: Technical aspects such as the need to support decoupling and recoupling from the main grid is still a challenge that needs further research;
- **Regulatory and Legal**: Depending on the country the current legislation may be preventing the adoption of LeM, for example some countries do not allow the installation of RES;
- **Economic**: Even though LeM have the potential to have financial benefits they still require an upfront investment for infrastructure, something that can prevent its adoption;
- **Stakeholder**: LeM requires the consumers to be interested in participating actively in the market, otherwise the adoption of the LeM cannot happen.

2.2.5 Approach by Ampatzis et al.

Ampatzis, Nguyen, and Kling 2014 consider the design of a LeM as a response to poor integration of DER, such as distributed energy storage and generation. Unpredictable generation, such as that from photovoltaic panels and wind turbines, is identified by the authors as one of the major challenges towards the integration of DER in wholesale markets that were not designed to handle such variable energy generation. Furthermore, DER cause bidirectional energy flow, something that the traditional energy gird was not designed to handle.

In his work, the authors identify a set of goals that they want their LeM to achieve. The LeM is based on a geographical area, such as a neighborhood. Consumption and generation of participants is measurable. The market does not suffer from transmission restrictions. The authors also identify the stakeholders in this market and their desires:

- **Consumer**: Wishes to reduce its energy cost without sacrificing energy needs;
- **Prosumer**: Wishes to maximize consumption from self-generation and profit from selling excess energy;
- **Market Operator**: Wishes to maximize the efficiency of the market.

The proposed market, takes into consideration: the bids format, clearing rule, pricing rule, and accessible information to participants. The authors propose a continuous double-sided auction with 15-minute dispatch interval. This LeM takes privacy as a focused point and so bids only includes quantity and price. Lastly, Figure 2.7 shows a flow chart representing the decision process used by this market to reach the final market price.

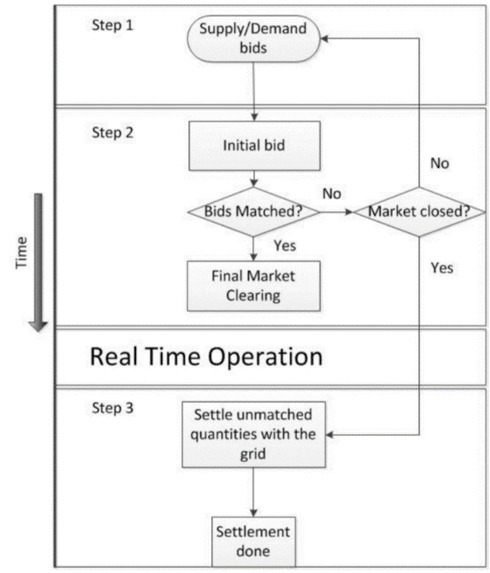

Figure 2.7: Market Operation Mechanism proposed by
Ampatzis, Nguyen, and Kling 2014

2.3 Forecasting in Energy Contexts

One of the techniques most used to study and to manage Energy systems is forecasting. The ability to make predictions with a considerable degree of accuracy and precision, within the context of energy systems is a desirable and helpful tool to model and improve simulations. Forecasting techniques for energy contexts have been studied by many authors that explore different methods. Understanding the forecasting techniques and the different methods is an important step to get a complete understanding of the task of simulating energy systems and markets.

2.3.1 Artificial Neural Network

Artificial Neural Network (ANN) Jain, Mao, and Mohiuddin 1996 is a form of machine learning that takes inspiration from the networks of neurons found in brains. Artificial Neurons can be on or off, The ANN is composed of several layers of neurons. Each layer has a specific purpose in the network. There are three kinds of layers that a ANN can have. The input layer receives the data to be processed. The output layer retrieves the final result after the data is processed by the network. In between these two layers there is one or more hidden layers. The hidden layer or layers are responsible for processing the data received from the previous layer. Neurons, except the ones in the input layer, can be on or off depending on the values received from the previous layer and on the weight given to each one of those connections. The ANN learns to produce better outputs through a process called back-propagation, where the weights for the connection between neurons are adjusted.

ANN were used in Deb et al. 2016 to forecast energy consumption for the purpose of cooling buildings during daytime. The target for this study were institutional buildings, such as universities, where the consumption can have a high variation due to the different schedules and vacation periods. In this study the authors developed a method that was able to make forecasting predictions up to 20 days in time.

In Murat and Ceylan 2006 the authors used a ANN approach to forecast energy demands for transportation using the Gross National Product (GNP) data as input. A case study was performed using historical energy data from 1970 to 2001. The authors concluded that their approach was successful in predicting the historical values and is suitable for future applications.

In Xiao Hong Yang et al. 2008 the authors explore energy consumption forecasting applied to the metallurgic industry. The method used was a ANN combined with a genetic algorithm Davis 1991, that is an algorithm that takes into consideration several solutions for a problem and combines some of them in order to obtain new solutions. The advantage of combining ANN with genetic algorithms is that local minimums produced by the ANN can be overcome by the genetic algorithm. The authors compared this approach with the single ANN approach and concluded that it obtains a higher precision and is faster than the single ANN approach.

2.3.2 Fuzzy Rule Base System

A Fuzzy Rule Base System (FRBS) Zadeh 1965 is system that uses fuzzy rules to make decisions. These are rules of type *IF x THEN y*, where x and y are defined by fuzzy sets. With fuzzy sets a given value might be only partially in a set. This characteristic of fuzzy rules makes them more versatile them Boolean conditions, as a result might be only partially true, mimicking what happens in the real world.

In Jozi et al. 2016 a combination of fuzzy rules with ANN was made in an approach called Hybrid Neural Fuzzy Inference System (HyFIS). The authors present a case study where this approach was used to forecast energy consumption with different inputs. Their results showed that with a combination of electricity consumption and the environmental temperature as input the HyFIS algorithm obtained the best results.

2.3.3 Reinforcement Learning

Reinforcement Learning Xu, Zuo, and Huang 2014 is a type of learning algorithm that works by rewarding correct actions and punishing bad ones. These algorithms act on top of Markov Decision Process (MDP). A MDP defines a problem in: a finite number o states S, a finite number of actions A, a probability for an action a in state s to result in a transition to state s' represented by $P_a(s, s')$ and a reward associated with each transition represented by $R_a(s, s')$. The objective of a Reinforcement Learning algorithm is to find the ideal action to perform for a given state in order to obtain the maximum reward.

In Rui Andrade et al. 2019 the authors applied the Upper Confidence Bound (UCB1), the Exponential-weight algorithm for Exploration and Exploitation (Exp3) and a simple Reinforcement Learning algorithm that only averages rewards over time. The objective of this work was to forecast the ideal action to take for the problem of energy management in a smart house. The case study performed considered 5 states, 5 actions with several probabilities of transition between states and a 24 hour simulation period. The results showed that over time all algorithms were able to learn the ideal strategy with the UCB1 algorithm achieving the best results.

In Kuznetsova et al. 2013 the problem of energy management in a micro grid is explored using the Q-learning Reinforcement Learning algorithm. The case study performed considered a consumer, wind generation, a battery and an external grid, in two distinct contexts. One with low wind generation and medium to high consumption, and another with high wind generation and low consumption. Their results showed that the Q-learning algorithm applied was able to achieve effective energy management.

2.3.4 Support Vector Machine

A Support Vector Machine (SVM) Vapnik, Golowich, and Smola 1997 is a supervised learning algorithm that operates with multidimensional data. This algorithm divides the data space with multidimensional planes that create clusters of similar data points. A SVM is able to approximate non-linear functions.

In Vinagre et al. 2016 the authors used different frameworks to apply a SVM method to forecast energy consumption in a Smart Grid. The authors concluded that a SVM model is a good approach for energy consumption forecasting.

2.3.5 Time Series Analysis

A Time Series is a group of sequential data points where the state of the previous points can influence the following ones. Shumway and Stoffer 2017. Time Series Analysis is the process of analyzing this data to extract valuable information, such as predictions for future values.

In Ediger and Akar 2007 the authors applied Time Series Analysis with the objective of performing forecasting of energy demand in Turkey. The methods used were Autoregressive Integrated Moving Average (ARIMA) and a variation called Seasonal Autoregressive Integrated Moving Average (SARIMA). The authors performed an analyzes on data from Turkey in order to predict demands from 2005 to 2020. This analyses indicated that almost all sources of energy would have an increase in demand. The authors concluded that the ARIMA and SARIMA can be effective in energy forecasting.

In Nogales et al. 2002 the goal was to perform energy price forecasting. The authors applied the Time Series Analysis models of dynamic regression and transfer function. The case studies were performed with real data from Spain and California. The case study for Spain used two weeks of hourly data, and for the California one week of hourly data was used. The results showed errors of 3% for the case study of California and 5% for Spain. The authors concluded that both models are viable options for energy price forecasting.

2.4 Security and Trust in Local Energy Markets

As discussed by several authors the Smart Grid is considered to be the physical basis for the LeM. One of the major concerns for any energy supply system must be security, and for the Smart Grid this is no exception. Security in the Smart Grid is indeed an active area of research. Several authors have analyzed and discussed parts of the Smart Grid that need special security care and/or bring potential security vulnerabilities. Although this dissertation is only focused on the Trust in negotiations aspect of security it is necessary to first understand security as a whole in order to propose a Trust model which can better play his role in the overall security.

Reliable network communications mechanisms is one of the fundamental parts for any Smart Grid and consequentially LeM. This is the central point of focus that authors present as security needs Ericsson 2010; Wang and Z. Lu 2013; Yan et al. 2012. The security concerns in communications are divided into 10 topics by Yan et al. 2012. These topics are the following:

- **High Level Security Requirements** - High Level Security Requirements refers to deliberate attacks and unintentional security issues. Deliberate attacks include physical attacks, such as terrorism and employee sabotage, and cyber-security attacks, such as Denial of Service (DoS), man-in-the-middle and others. Unintentional security issues are events which are not direct attacks but can compromise the security. These include hardware failures, user errors and even natural disasters;

- **Privacy** - Privacy is in general a big concern in today's society. In the context of the Smart Grid and LeM, privacy needs to be taken seriously. The information such as consumption gathered by sensors can be used to extrapolate users behaviors and activities. The issue of privacy is more than a technological issue and is dependent on political action to create the adequate laws and regulations;

- **Availability** - Availability concerns are present in the Smart Grid and LeM context. The energy supply is a critical system and down time can have impacts ranging from private consumers and business to health organizations and law enforcement. The technological nature of the Smart Grid creates a new vector of attack with DoS attacks that can stop the energy supply. Yan et al. 2012 indicates that in the Smart Grid network the delay of data is the biggest potential issue due to the time constraints of the information;

- **Integrity** - The Integrity of data is a pillar of security in computer and communication systems that deal with sensitive data. Unauthorized parties need to be prevented from modifying data. Modified data can be used to attack the control systems in the Smart Grid, thus making them behave in an undesirable way;

- **Authentication** - The Authentication aspect of security deals with correctly identifying real system participants and distinguish them form illegitimate impersonators;

- **Authorization** - Authorization is closely related to Authentication, and the two complement each other. While Authentication deals with the identification of users. Authorization is concerned with identifying what said user is or is not allowed to do within the system. For example a regular user should not have administrative authorization in a system;

- **Auditability** - The Auditability of a system is the ability to analyze and understand the historic data of a system. When preforming and auditing the objective it to find attacks that previously passed unnoticed or understand how an already known attack happened. Auditability is not an active security measure but a reactive one. However it is crucial to understand failures or security flaws and prevent them in the future;

- **Non-repudiability** - The Non-repudiability of data is the ability to demonstrate with absolute and irrefutable certainty from who or where data is originated. Non-repudiability is an important factor of accountability. If a certain malicious action is taken in the LeM it is necessary to identify and take action to deal with the culprits;

- **Third-party Protection** - Third-party Protection takes into account the security concerns that a compromised system can have to third parties. By targeting third parties through the Smart Grid control system the Smart Grid can be liable for the damages done. This is an indirect attack that also can have negative consequences to the

Smart Grid and LeM. This being the case the security of third parties needs to be taken into consideration;

- **Trust** - Lastly Yan et al. 2012 identifies the concerns of trust in the system itself. Systems are often divided into many parts. Some are new some are old and the software is written by different people in different programming languages. This distributed nature of the system development is a necessity due to the scale of a Smart Grid and the need to integrate with legacy systems. For these reasons security needs to be seen as a multi-layer approach, making a combination of hardware monitoring and applying different software security methodologies to secure the system as a whole.

It is important to understate that in this last point of Trust is referring to an issue different form the one being studied in this thesis. Yan et al. 2012 talks about trust in the systems in the broader sense. While the definition of trust studied here is of trust within the LeM negotiations.

This concept of trust in the LeM negotiations arises from the need to ensure that participants and their participation are real and trustworthy. Untrustworthy participation is undesirable as it can influence the market result in a negative way. Untrustworthy participation can be intentional or not.

For example producers and prosumers who wish to sell energy in the market could propose to sell more energy that they can produce in order to gain a financial advantage. Other examples of untrustworthy behavior can occurs due to some form of hardware failure, such as a sensor reporting wrong values.

In a way Trust in the LeM negotiations is connected to several of the points presented by Yan et al. 2012. Market participation must only be made by Authenticated and Authorized participants. Participation needs to be non-repudiable. Integrity of data and trust, in the system as presented by Yan et al. 2012, are also crucial for trusted negotiations. One important point in Integrity within the context of Trust in LeM negotiations is that, as described, the participant itself may attempt to modify data in an undesirable way, so this must be taken into account when designing a Trust model for this context.

2.5 Multi-Agent Systems Concepts

The IEEE Power and Energy Society IEEE-PES n.d., which is part of the Institute of Electrical and Electrotechnical Engineering (IEEE) created a working group called IEEE Power and Energy Society multi-agent systems working group IEEE n.d.(a) responsible for presenting and defining standards for the usage of Multi Agent Systems within the context of power systems applications. This states very well the relevance of MAS in the scope of Power and Energy systems.

A MAS can be defined as a system that combines a group of agents that together are able to achieve goals that otherwise would not be possible to achieve without the combination of efforts Wooldridge 2009. To fully understand the concept of a MAS, it is first necessary to grasp the idea of a single Agent.

An Agent, in its broadest definition, is described as an entity that is capable of making observations and performing actions upon its world or environment in an autonomous way. Russell and Norvig 2009 identify these observations and actions as being performed by sensors and effectors, respectively. As Russell and Norvig 2009 pointed out, such definition can be applied to a wide range of scenarios. Everything from humans and animals, to robots and to pieces of software can be viewed as an Agent, however in the context of a MAS we are only focusing on the latter, that is software Agents.

Russell and Norvig 2009 also presented the idea of a rational Agent, that is, an agent that aims towards selecting its actions ideally in order to solve problems. It is important to make a distinction between such an agent and an ideal rational agent. The ideal rational agent always performs the absolute ideal actions in every scenario, while a rational agent may or may not perform the absolute ideal action depending on its limitations at any given time. These limitations can come from a lack of relevant knowledge, unpredictability of certain events, or other factors.

This definition of an Agent is also in line with the one presented by IEEE n.d.(b), where the term intelligent agent is used instead of rational agent. The intelligent agent is also described as having three main characteristics:

- **Reactivity**: the agent responds to changes in the environment in the appropriate time;
- **Pro-activeness**: the agent takes initiative when necessary in order to achieve its goals;
- **Social ability**: the agent is capable of interacting, negotiating and cooperating with other agents. This is usually done by agent communication language Agent Communication Language (ACL) messages.

2.6 Multi-Agent Systems Development Platforms

MAS are complex and their development is not a trivial task. Using an agent development platform that implements some of the lower level tasks such as network communications, is a way to facilitate its development. Furthermore, a well-designed development platform can improve standardization and compatibility among projects. Several MAS Development Platforms have been developed since MAS became a topic of interest. In Leon, Paprzycki, and Ganzha 2015 an analysis of the available options for MAS development was performed. The authors identify several projects, however some projects such as: ZEUS Nwana et al. 1999, AgentBuilder AgentBuilder n.d., Open Agent Architecture International n.d. and others have become inactive or have little information available. Choosing the appropriate development platform is an important step to take into consideration. For this reason, the following Sections present the requirements that the selected framework must fulfill, an analysis of several MAS development platforms and a comparison in order to understand which one is best suited for this project.

2.6.1 Framework Requirements

The framework chosen needs to fulfill the three following requirements.

Security Oriented

The Local Energy Market (LeM) developed in this thesis will rely heavily in computer systems and network communications. For this reason, there is a need to ensure that the information of the participants, their energy generation and consumption data, their interactions in the LeM and their identity are kept secure. That is, no unauthorized parties can access information, and no one can impersonate someone else. The security requirements for computer systems that deal with sensitive information is a critical field of study in computer science. Wang and Z. Lu 2013; Yan et al. 2012 identify five security principals that computer systems and particularly Smart-Grids should follow in order to ensure the overall safety of users and information. These security principals are:

- **Confidentiality**: Refers to the need to maintain private information as private, and just accessible to the authorized parties;
- **Availability**: The need to maintain services and infrastructures available and working correctly;
- **Authentication**: Ensuring that every party of interest in a communication is who it claims to be;
- **Integrity**: The need to maintain information safe from being modified or corrupted by unauthorized Parties;
- **Non-repudiation**: Ensuring no party has the ability to deny being the author of any action done by him.

Security will play an important role in the success of LeM. The chosen framework needs to provide security-oriented features.

FIPA compliant

One of possibilities in consideration for project Secure interactions and trusted Participation in local Electricity Trading (SPET) is the integration of the LeM MAS with MASCEM, presented in Section 2.7.4. MASCEM follows the FIPA standard FIPA n.d. which makes it compatibly with other MAS that are also FIPA compliant. For this reason, the chosen framework must be FIPA compliant.

Platform support

As already described some frameworks used in the past have become inactive and unsupported. Choosing a framework with solid support is an import consideration both for this dissertation and for SPET project.

JACK

JACK is a cross-platform MAS development platform JACK n.d. It is developed in java and takes focus on portability and scalability. JACK follows the Belief Desire Intention (BDI) model which contains the following elements:

- **Beliefs**: Information that the agent has access to;
- **Desires**: States of the world that the agent considers desirable;
- **Intentions**: States of the world that the agent as decided to pursue.

JACK appears to be under active development however it is a commercial solution. JACK does not provide any information in FIPA compliance or security features.

Janus

Janus is a MAS development platform Janus n.d. Developed with SARL Rodriguez-Fernandez et al. 2018, a general-purpose agent-oriented programming language with java interoperability. Janus also follows the BDI model and supports network distributed applications. Janus follows the FIPA standards for agents and agent-based systems standard. Janus is under active development as the default SARL runtime environment and is open source. No information about security features was found.

JADE

Java Agent DEvelopment Framework (JADE) JADE 2019 is an open source MAS development framework, implemented in the java programming language. JADE also provides support for distributed scenarios out of the box. This is done by separating agents into containers that execute on different machines, as shown in Figure 2.8.

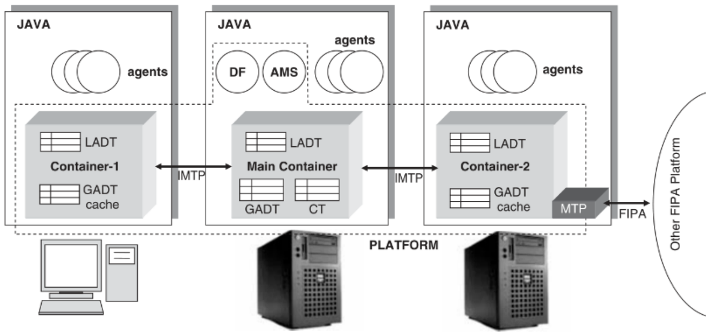

Figure 2.8: JADE architecture
Bellifemine, Caire, and Greenwood 2007

JADE follows the FIPA standards for agents and agent-based systems. It offers security oriented features via an extension Board 2005. JADE as also been in active development since 1998 Bellifemine, Caire, and Greenwood 2007 and is open source.

Final comparison of available Platforms

The platforms described show differences: JACK as a commercial solution, Janus that is supporting an agent focused programming language, and JADE as a long-standing platform that remains active and receiving updates. These platforms are compared in Table 2.1.

Table 2.1: MAS Platforms comparison

Platform	Security oriented	FIPA Compliant	Platform support
JaCK	No information	No information	Active development, Commercial only
Jamus	No information	No information	Active development, Open source
JADE	Yes	Yes	Active development, Open source

JACK as a commercial platform and with no information provides about security or FIPA compliance does not seem appropriate for this use. Jamus seems an interesting option but it does not appear to provide security-oriented features. Ultimately the chosen platform will be JADE, since it is in line with all the requirements of the project.

2.7 Multi-Agent Systems in Energy Markets

Several MAS have been developed in energy related contexts. The following Sections describe a few MAS that work in this context.

2.7.1 EMCAS

Electricity Markets Complex Adaptive System (EMCAS) Koritarov 2004 is an agent-based modeling and simulation tool, designed to model and simulate the behavior of participants in electricity markets. One of the focuses in EMCAS is to capture the heterogeneity in electricity markets. To do this EMCAS includes a variety of market entities that can be represented by agents: Generation Companies (GenCos), Demand Companies (DemCos), Transmission Companies (TransCos), Distribution Companies (DistCos), Independent System Operators (ISOs), consumers, and regulators.

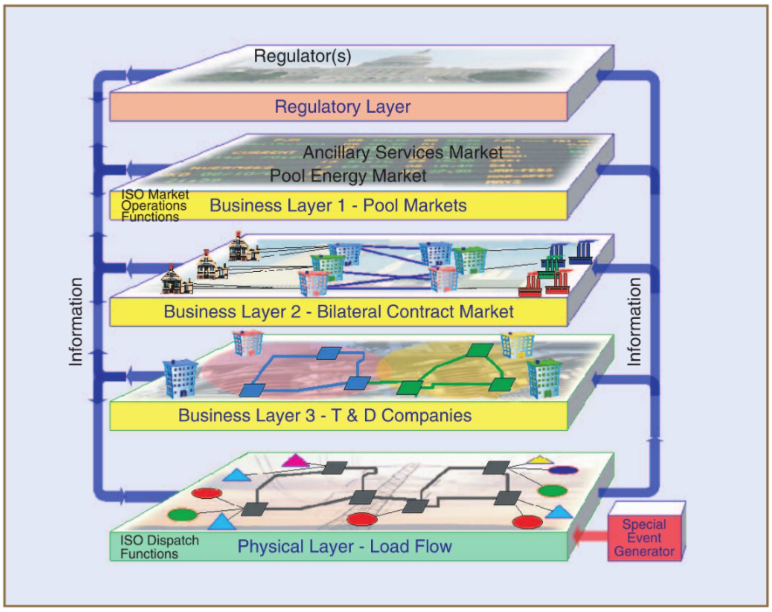

Figure 2.9: EMCAS Simulation Layers
Koritarov 2004

Agents in EMCAS are modeled to apply two kinds of learning behaviors: observation based, and exploration based. Observation based learning examines historical data, the behavior of other agents, and predictions for the future. With this data the agent chooses its strategy. On the other hand, exploration based learning works by trying various strategies and finding the one that seems most beneficial. As for the structure of EMCAS it is of 5 distinct layers, represented in Figure 2.9, and agents are able to operate in several layers. These layers are the following:

- **Regulatory Layer**: Represents the regulations and rules of operation in the market;

- **Business Layer 1**: Operates at the level of auction-based markets;
- **Business Layer 2**: Operates at the level of establishing bilateral contracts;
- **Business Layer 3**: Represents the transmission and distribution companies and takes into consideration the fees necessary for these companies' services;
- **Physical Layer**: Represents the physical electricity grid, including physical generation, transmission, distribution, and consumption of electricity.

2.7.2 AMES

AMES Li and Tesfatsion 2009 is an open-source agent-based tool, developed to simulate and research wholesale power markets that follow the U.S. Federal Energy Regulatory Commission (FERC) design. AMES architecture has the following 4 simulation features:

- **Traders**: Supports the simulation for large scale buyers called Load-Serving Entities (LSEs) and sellers called Generation Companies (GenCos);
- **Negotiation**: Supports the simulation of a Real-time market or Day-ahead market;
- **Transmission grid**: Simulates the energy transmission in the grid;
- **ISO**: Manages the operations in the power grid.

The AMES system operates by having continuous communications between the traders and the ISO, as presents in Figure 2.10. GenCos can send offers and LSEs can submit bids, both to the ISO. Then ISO performs the market closing operations and sends back the results. In this operation GenCos Agents in the AMES system are capable of using stochastic reinforcement learning techniques in order to learn the optimal way to act in the market.

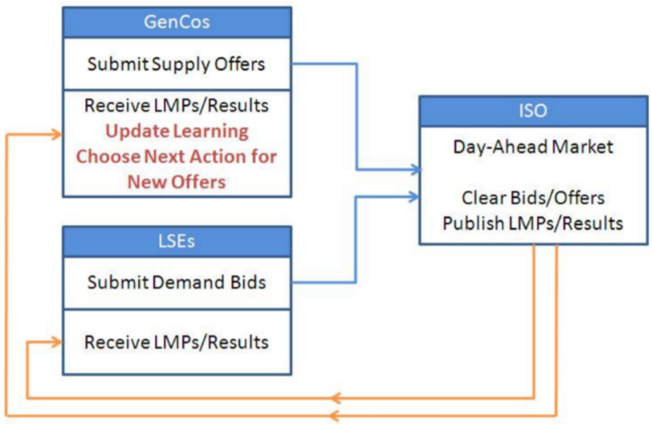

Figure 2.10: AMES negotiation flow
Li and Tesfatsion 2009

2.7.3 GAPEX

Genoa Artificial Power Exchange (GAPEX) Cincotti and Gallo 2013 is a MAS developed in MATLAB MathLab 2019. The GAPEX framework targets the modeling and simulation of power exchanges. GAPEX operates at the level of auction-based markets and the research has showed that it is capable of performing accurate simulations of European power-exchanges. One market that was simulated with the GAPEX framework was the Italian Electricity Market Cincotti and Gallo 2013.To simulate this market it was necessary to implement the following main components:

- An agent that represents the Italian Electricity Market Operator responsible for enforcing the current market negotiation rules;
- An agent that represents the Italian electrical grid;
- Agents that represent the participants:
  - GenCos: generation companies;
  - Loads: aggregated electricity demands;
  - Market Operator: Manages the negotiation communications;
  - Clearing House: Calculates the clearing price for the market.

Agents in GAPEX also act accordingly to a reinforcement learning model. The agents use an enhanced version of the Roth and Erev algorithm Roth and Erev 1995. This learning model allows agents to learn and adapt their biding strategy to perform better in the market.

2.7.4 MASCEM

Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) Praça et al. 2003; Santos et al. 2016 is a FIPA compliant MAS, developed with JADE, described in Section 2.6.1, focused on simulating electricity markets and the interactions between their participants. The simulated markets can have several distinct models, for example MASCEM Z. Vale et al. 2011 is capable of supporting simulations with wholesale markets or bilateral contracts. To be able to model the complex interactions of electricity markets MASCEM utilizes an agent model with various distinct agents Oliveira et al. 2009. These agents are the following:

- **Market Facilitator Agent**: The Market Facilitator Agent is responsible for identifying and managing all the agents that participate in the market;
- **Seller Agents**: Agents that participante in market negotiations with the intention of selling electricity;
- **Buyer Agents**: Agents that participante in market negotiations with the intention of buying electricity;
- **Trader Agents**: Agents that participante in market negotiations on the behalf of other entities;
- **Virtual Power Player (VPP) Agents**: Agents that participante in market negotiations while represent a several agents;
- **VPP Facilitator Agent**: The VPP Facilitator Agent is similar to the Market Facilitator Agent but only manages agents that are part of a VPP;
- **Market Operator Agent**: Responsible for applying the rules for each specific market. This Agent receives the negotiation proposals and applies the double-sided auction to obtain the final price;

- **System Operator Agent**: Represents the ISO who is responsible for managing the power transition on the agreed negotiations;
- **Market Regulator Agent**: Assumes the role of introducing changes to the market rules when necessary.

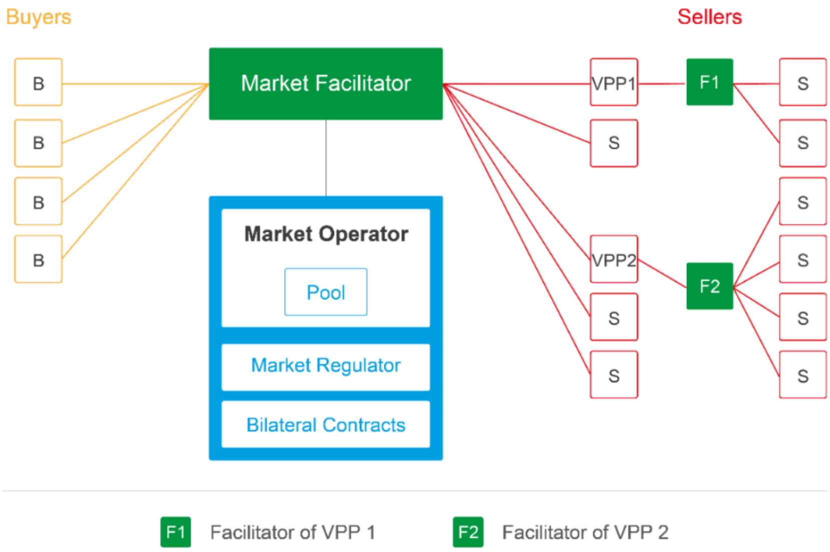

Figure 2.11: MASCEM Agent Model
Z. A. Vale et al. 2012

With this agent model presented in Figure 2.11 MASCEM can be used to simulate complex interactions in electricity markets, simulate the effects that changes can introduces in real world electricity markets and can perform decision support for participants that also operate in real world markets.

2.8 Trust in Multi-Agent Systems

Trust, as expressed in the OxfordDictionaries n.d. dictionary is: "Firm belief in the reliability, truth, or ability of someone or something". In the context of a negotiation trust is viewed as the reliability that the opposing party or parties will carry out what was agreed upon during the negotiation. One of the areas where the lack of trust can be a major problem is in e-commerce Rahimi and Bekkali 2017. Trust is a fundamental need in a negotiation, if two or more interested parties want to make an agreement but cannot trust each other, then such an agreement might be impossible or at least partially compromised. Trust and Security are highly intertwined G. Lu et al. 2009, that is information cannot be trusted in an unsecured system. However, even in a secure system, a legitimate participant might try to send false information. In the context of a LeM this can be thought of as a participant that makes a proposal trying to influence market price, and not according with the amount of energy he can really offer.

Rahimi and Bekkali 2017 presents an overview of Trust and Reputation Systems (TRS) with an emphasis on their application in e-commerce scenarios. TRS are designed with the objective of predicting the reliability in the behavior of an entity by analyzing data from past interactions. By preforming such an analyzes TRS are able to associate a reputation to each user. Good reputation indicates that the user is trust worthy in its negotiations, and vice versa.

Houser and Wooders 2006 views this problem from the perspective of eBay. eBay operates as an online auction web site. Users of this platform can propose their sale offers and/or place bids on other users' offers. In online auction web sites such as eBay the participants in the transactions are humans and these platforms implement mechanisms for participants to review their experience in the transaction. This feedback provided by the users is then used to feed the TRS with the data necessary to access the reputation of the users Rahimi and Bekkali 2017.

Sabater and Sierra 2005 presented a general overview of trust and reputation computational models. In this work Sabater and Sierra 2005 express that, aside from the importance in e-commerce acceptance, trust also plays an important factor in the context of MAS. The authors also make a detailed explanation of trust and reputation computational models and define a set of classification dimensions for these models. These classification dimensions are the following:

- **Conceptual model**: Conceptually the trust and reputation model can be classified as Cognitive or as Game-theoretical:
  1. Cognitive: In the cognitive based trust, the agent's beliefs are the major factor when deciding whether to trust another agent or not;
  2. Game-theoretical: The Game-theoretical model views trust as a probabilistic function. The decision to trust or not another agent is made as a probabilistic calculation based on past interactions;
- **Information sources**: classification of the sources of information used to compute trust and reputation:
  1. Direct experiences: Sources of information that were gathered directly by the agent;
  2. Witness information: Information received from other agents in the community;
  3. Sociological information: Information gathered from the relations established by agents. These models analyze the relations between agents as a Social network and analyze them similarly to how humans use information from social relations;
  4. Prejudice: Attributing different levels of trust to agents depending on groups that the agent might belong to;
- **Visibility types**: The Visibility dimension classifies how agents manage their trust and reputation views as a group:
  1. Individual: individual trust and reputation values refers to systems where each agent makes its own decision whether or not to trust another agent;
  2. Public: a public approach creates a global trust value for each agent by aggregating the information of all the interactions that agent had with other agents;
- **Model's granularity**: The Model's granularity dimension expresses the degree to which the trust and reputation in a computational model is taken as a general characteristic of the individual or agent, or if its trust and reputation differ depending on the situation:

1. Single-context models: Represent the trust and reputation of an agent as a single value, considered despite the scenario. With a single-context approach, an agent that is trusted for an action A, will be equally trusted for action B;
2. Multi-context models: Represent the trust and reputation of an agent as multiple values, each associated with a scenario. With a multi-context approach, an agent that is trusted for an action A, may or may not be trusted for action B;

- **Agent behavior assumptions**: this dimension considers the way that the computational trust and reputation model responds to malicious information:
  1. Level 0 is described as an approach that does not consider any kind of malicious behavior. These models often operate in scenarios with a large number of participants and take advantage of this large number in order to mitigate the malicious ratings;
  2. Level 1 models assume an intermediate approach, where the assumption is that some information might be omitted, while also assuming the absence of false information;
  3. Level 2 approaches are the most defensive, in the sense that assume some participants might be liars, and have measures to deal with them;
- **Type of exchanged information**: Differentiates which kinds of information is provided from other agents:
  1. Boolean: Commonly used in probability-based approaches;
  2. Continuous: Commonly used in scenarios where the trust and reputation model rely on aggregation mechanisms;
- **Trust/Reputation reliability measure**: The final classification dimension is the reliability measure and it classifies the trust and reputation models as having or not a reliability measure value that indicates how reliable the trust and reputation value is expected to be.

Regarding the Visibility types Sabater and Sierra 2005 identify public approaches as ideal for scenarios where there is a very high number of participants (thousands or more) and multiple interactions between the same pair of agents are uncommon. By contrast the individual approach is targeted at scenarios where the number of agents is smaller, and agents interact multiple times with the same agent.

In another review work Rahimi and Bekkali 2017 identify several trust models, some of which are specific for the Marketplace area of applicability. Two of these trust models seem interesting for this project since they are targeted at a marketplace but apply different strategies. These models are the e-commerce model, specifically eBay (eBay, no date d) and ReGreT Sabater and Sierra 2001.

2.8.1 E-commerce trust models

E-commerce trust models are specialized for targeting online actions. Two of the largest online action websites Amazon Amazon n.d. and eBay EBay n.d.(d) make use of such models. Online action websites implement trust mechanisms that improve costumer trust and help drive purchases Ow et al. 2018. One such mechanism implemented by eBay is, sellers who are identified as malicious have their ability to sell blocked. This mechanism improves buyers trust in the sense that it shields customers from malicious sellers and helps honest sellers that can gain customers trust in their reliability and possibly charge higher prices due to that trust Ow et al. 2018. This mechanism is based on eBay's feedback system, EBay n.d.(a). eBay's feedback is bidirectional, feedback can be given to sellers EBay n.d.(c) or to buyers EBay n.d.(b) and both forms of feedback are voluntary. Feedback for sellers is given in 3 options for rating: positive (1), neutral (0) and negative (-1), customers can also further detail their experience with the seller with additional information about the transition and a written comment. A sellers overall rating is represented as a percentage based on the mean of these ratings. As for feedback given to buyers can only be given as positive and with an accompanying comment. This feedback can be seen in the user's feedback profile, unless the user has made his feedback profile private EBay n.d.(a). Accordingly to eBay EBay n.d.(a) only users with public feedback profiles can be sellers.

According to Sabater and Sierra 2005 Online trust models are classified as: Game theoretical, Witness information, Public, Non-context dependent, Level 0 assumptions, do not use Boolean information and do not have a reliability measure.

2.8.2 ReGreT

ReGreT is a trust and reputation model proposed by Sabater and Sierra 2001. This model is different from the eBay model because it does not consider trust as a global value. ReGreT has a focus towards modularity. Sabater and Sierra 2002. Modules might be used or not depending on the needs of each context. ReGreT considers three kinds of information for trust: the agent own experiences, information from other agents and the social structure among agents. These types of information coincide with the three dimensions used in ReGreT to calculate trust, which are the following:

- **Individual dimension**: Considers the outcomes observed directly by the agent when in negotiation with another agent. The Outcomes are stored in the Outcomes Data Base (ODB) and contain the information on what values were agreed and what values were actually delivered. ReGreT model uses the Outcomes information to calculate the individual reputation, which is presented by the authors as being the most reliable;
- **Social dimension**: Considers information provided by other entities. Something can be useful when direct information is not available. The social dimension is composed of the following three kinds of reputation:
  - Witness reputation: Witness reputation is a reputation value that is based on information provided by agents that have interacted with the target agent;
  - Neighborhood reputation: Neighborhood reputation is a reputation value that is based on the reputation of other agents that are closely linked with the target agent;
  - System reputation: System reputation is a default reputation values that is based on the type of agent;
- **Ontological dimension**: Considers the contextual information that can be gained by the reputation. As an example, an agent that has a good reputation for solving mathematical equations can be expected to have a good reputation for performing addition and subtraction operations.

According to Sabater and Sierra 2005 ReGreT is classified as: Game theoretical, Direct interaction, Direct observation, Witness information and Sociological information, Individual, Context dependent, Level 2 assumptions, do not use Boolean information and have a reliability measure.

In another work Pinyol and Sabater-Mir 2013 expressed the idea that trust in a MAS environment is an important factor for its success. The authors identify three distinct approaches that can be followed when developing a trust mechanism for a MAS. Each approach considers a different dimension of trust. These approaches are:

- Security Approach: This approach is focused on the traditional security mechanisms mentioned in Section 2.6.1: confidentiality, availability, authentication, integrity, non-repudiation. This dimension aims to prevent cyber-security threats;
- Institutional Approach: This approach considers the idea of a centralized entity that acts as an overseer in the MAS. This centralized entity, takes the place of an institution that must evaluate all agents and ensure that each one of then is trustworthy. It is also of the responsibility of the central entity institution the need to take a corrective action or even block bad agents from participating in the MAS;
- Social Approach: Lastly, the social approach, is similar to the way humans interact in the real world. With this trust model each agent decides who it considers trustworthy. Agents can make this decision based on their interactions with each agents and/or by considering opinions of other agent.

2.9 Overview

This chapter covered all the concepts necessary to understand the context of the problem addressed. Energy markets and contract types made in these market's negotiations, as well as an analysis of the LeM, and approaches by various authors to model LeM were described.

An analysis of various forecasting methods and their uses in the energy context was also performed; an analysis of security and trust concepts relevant to the context of the LeM; as well as an analysis of the concepts of the MAS, and the framework available for its implementation. Different MAS developed in the context of energy markets were also addressed. Finally, different trust mechanisms that could be used in MAS were explored.

Based on the information presented here, the next chapter discusses the design of the solution and its development.

Chapter 3

Solution Design and Development

To simulate a complex environment such as a Local Energy Market (LeM) and its interactions it is first necessary to define some clear objectives and assumptions so that the process of designing the system can follow those requirements. This section presents the considerations and assumptions made for the model in Section 3.1 And the proposed model is described in Section 3.2. Section 3.3 describes the development of the solution. Section 3.4 describes the trust model. Lastly, Section 3.5 presents an overview of the chapter.

3.1 Assumptions and Considerations

When considering the design of such a complex system the possibilities are immense. Before proposing a solution, defining assumptions about the problem's environment is a way to establish a base on which the model can be built upon. The assumptions made about the environment are the following:

- **A1**: The LeM operates in a limited physical area;
- **A2**: The LeM operates with a relatively small number of members;
- **A3**: The consumer participants desire to minimize their financial cost without sacrificing their energy consumption;
- **A4**: The participants may operate with malicious intent by sending false information in order to exploit the market in their favour;
- **A5**: Hardware failures may occur leaving their participants with incorrect information.

With these assumptions in mind, two possible ways for structuring and designing the LeM need to be considered. These two possibilities are a LeM based on bilateral contracts, or a LeM based on mediated contracts, both presented in Section 2.1.2. Before choosing the design that better fits the LeM needs, it is necessary to analyze each one.

Bilateral contracts market model operates in a more decentralized way, agents would be able to negotiate directly with each other by communicating directly, as illustrated by Figure 3.1. However, the bilateral contract poses some incompatibilities with the market model for project Secure interactions and trusted Participation in local Electricity Trading (SPET), a market modeled in such a manner would go against one of the main objectives in the SPET project which is the creation of a Market Interaction Manager (MIM) agent that manages the local market, and ensures the security and trust in the transactions. Other concerns in this approach come from the fact that no central authority would be responsible to assure that participants are trustworthy, leaving the task of finding trustworthy business partners

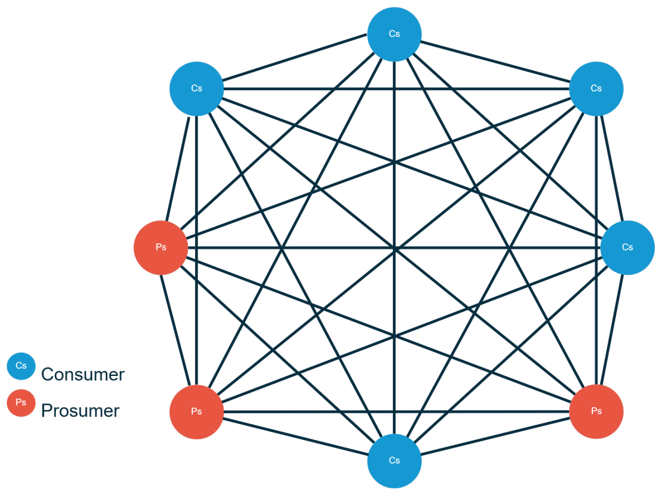

Figure 3.1: Decentralized Market concept

up to participants themselves. On the other hand the mediated market model approach, as shown in Figure 3.2, appears to be more in line with the project SPET requirements. Firstly, the concept of a mediated market contains by default a central authority that takes the role of a mediator in the market transactions. Such a role fits precisely with the idea of the MIM agent presented in SPET project objectives. Furthermore, with a more centralized market approach, the communications and data from the market would be aggregated by the market mediator, with this data the market mediator can perform data analysis to discover what market participants are trustworthy or not, and thus ensure an healthy negotiation environment.

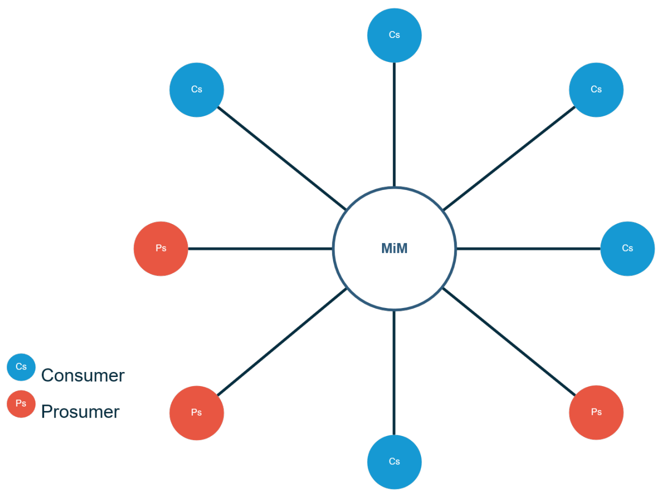

Figure 3.2: Centralized Market concept

3.2 Proposed MAS LeM Model

A computational model of LeM that respects the requirements previously expressed is here proposed. This model takes inspiration from the models proposed in the literature, in Section 2.2, and presents ideas in order to try to solve the challenges of this project. This model is based on a Multi-Agent System (MAS), where several types of agents will participate in order to fulfill market needs. The agents are the following:

- **Sensor agent**: Has the single responsibility of acquiring one type of data and reporting said data to his respective Participant Agent. A Sensor agent can be, for example, connected to a meter measuring energy consumption in a household, while another sensor agent can be connected to a web service in order to obtain the weather forecast;
- **Participant agent**: Acts on behalf of consumers, producers or prosumers. This agent assumes the role of a negotiator that seeks to best satisfy the needs of the respective market participants (home owners, local commerce and small industry owners). The Participant Agent will have Sensor Agents that report to him the information needed for the negotiations. The Participant Agent is then able to make proposals to buy or sell energy in the market;
- **Market Interactions Manager**: Is at the center of every LeM and is responsible for managing all negotiations within the market. The task of ensuring Trust in the negotiations is also a responsibility of the MIM.

With this 3 kinds of agents it is possible to create a reasonably complete representation of a LeM. It is possible to represent all three kinds of participants, that is consumers, producers and prosumers. The Sensor Agents allow the cyber-physical system, such as the ones of Smart Houses and other connected environments. A complete representation of the proposed LeM model is presented in Figure 3.3.

The LeM is composed of several participants, represented by their respective Participant Agent and all of these agents are connected to the MIM Agent. In Figure 3.3 three participants are further detailed as examples of how real participants might be structured in a realistic scenario. These participants are the following:

- **Consumer**: The consumer is representing a household that participates in the market. This house does not have any form of generating its own energy. In this example such a participant is connected with two Sensor Agents. One of the Sensor Agents gathers data on energy consumption and the other gathers data on the weather. Consumption data is relevant to create an historical profile to predict future energy needs and for negotiations. Weather data is relevant because it gives contextual information that can help to improve energy needs predictions, for example if temperatures drop it is expected for consumption to rise due to the need of warming the house;
- **Prosumer**: The prosumer is representing a household that participates in the market and has its own energy generation, with a small wind generator. This participant has the same Sensor agents as the consumer one, plus it includes a Sensor Agent for gathering data on energy generation. Consumption data is relevant to create an historic profile to predict future energy needs and for negotiations. Generation data is relevant to create an historic profile to predict future energy generation and for negotiations. Weather data is relevant because it gives contextual information predictions for consumption and for generation, based in data such as wind speed;
- **Local Solar Power Plant**: The other participant is the local solar power plant. This participant exemplifies a small photovoltaic power plant that participates in LeM. In this case, there are Sensor Agents for generation and weather data. Generation data is relevant to create an historic profile to predict future energy generation and for

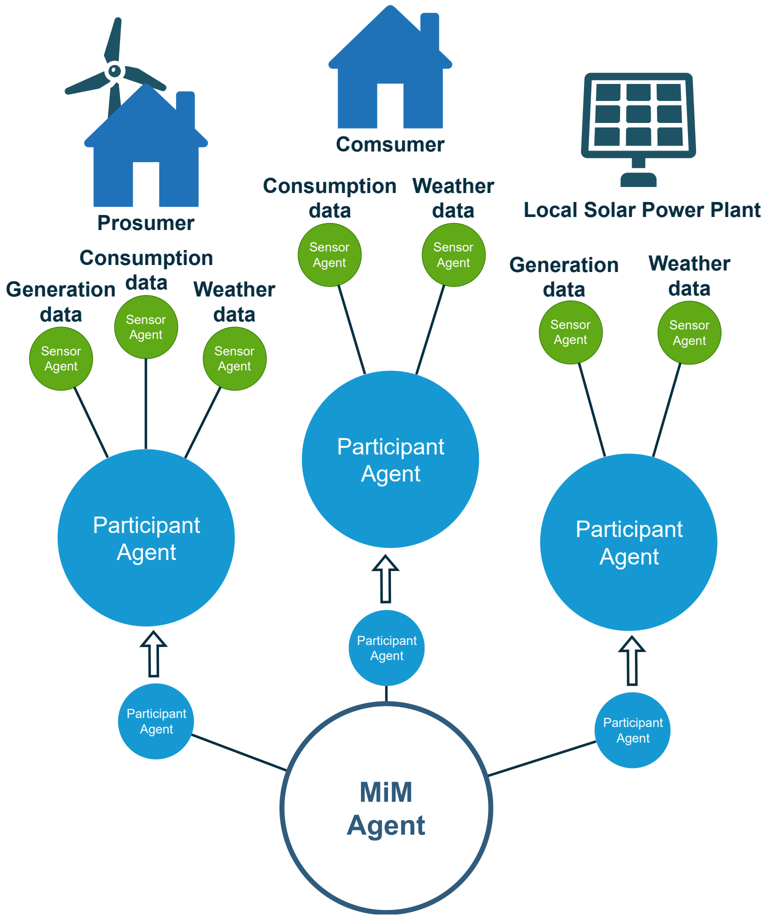

Figure 3.3: Proposed LeM model diagram

negotiations. Weather data is relevant because it gives contextual information to predict generation with data such as sunlight forecast.

With the proposed agent model each agent will have its own responsibilities within the overall market simulation.

MIM agent responsibilities:

- Takes the responsibility of starting every market negotiation period;
- Will work as a time synchronization mechanism for the simulation. This is because agents communication can occur in unpredictable sequences;
- Takes the responsibility of performing the trust evaluation for the participants;
- The MIM agent must also perform the energy trading for example it can follow the double auction trading scheme, as proposed by several authors Abidin et al. 2016; Ampatzis, Nguyen, and Kling 2014; Bremdal, Olivella, and Rajasekharan 2017 in the literature described in Section 2.2;

Participant agent:

- Takes the responsibility to answer to the MIM agent participation requests;
- Takes the responsibility to request updated values to its sensor agents;

- Takes the responsibility to evaluate his own energy needs and desire to buy or sell energy.

Sensor agent:

- Takes the responsibility to answer to the Participant agent request for updated values.

With this Local Market model and the defined responsibilities for the agents we obtained the following market simulation sequence shown in Figure 3.4. As the figure shows the simulation is an iterative process. This process starts with the MIM agent that sends a *Call for Proposal* request to the Market Participants. Once the participant receives the *Call for Proposal* it will send a *Request for Updated Reading* to his Sensor agents. Upon receiving this *Request for Updated Reading* the Sensor agents report their most recent value.

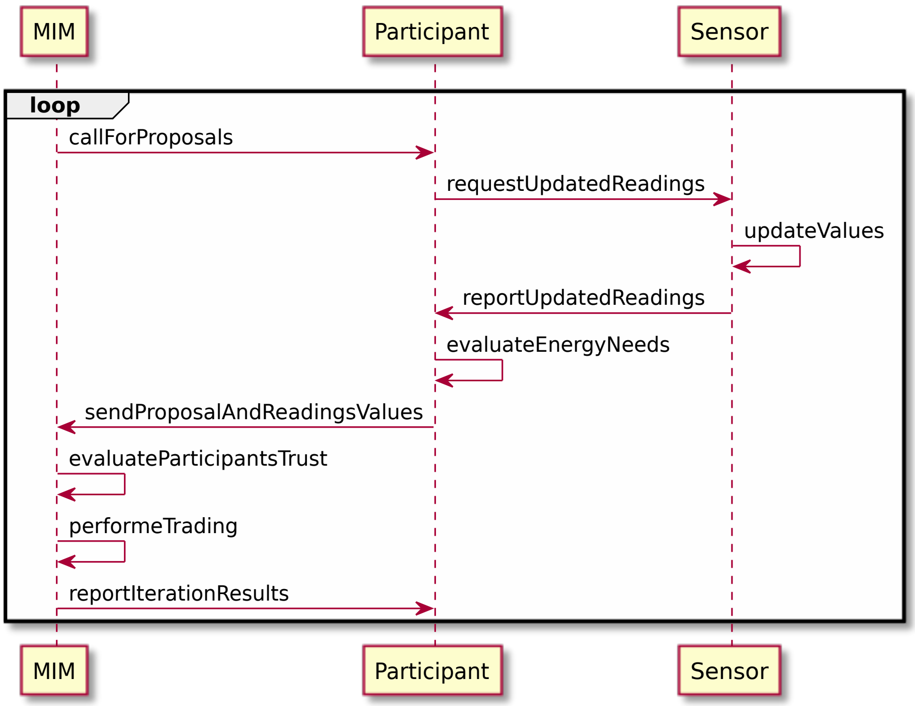

Figure 3.4: Market Negotiation Process

3.3 Development

This development aimed to followed good practices and adequate design patterns. The objective is to obtain a robust and yet flexible MAS system that can accommodate the necessities of the project.

3.3.1 Agents Development

In the JADE platform, agents are implemented by extending an Abstract Agent class which is part of the JADE core. This class was further extended in another abstract class with aspects that was common to all LeM agent. This avoids duplicated code and provides a solid basis for future development.

```java
public abstract class LeMAgent extends Agent {

    protected ACLMessage message;
    protected abstract void processLeMessage(LeMMessage lemMessage);

    private void processReceivedMessage(ACLMessage message) {
        LeMMessage lemMessage = null;
        try {
            lemMessage = (LeMMessage) message.getContentObject();
        } catch (UnreadableException e) {
            e.printStackTrace();
        }
        processLeMessage(lemMessage);
    }

    public CyclicBehaviour cyclicMessageReceive() {
        return new CyclicBehaviour() {
            @Override
            public void action() {
                message = this.myAgent.receive();
                if (message != null && !verifyAMS()) {
                    processReceivedMessage(message);
                } else {
                    block();
                }}};
    }

    public void sendMessage(int aclPerformative, LeMMessage msg, String
    Id) {
        ACLMessage aclMessage = new ACLMessage(aclPerformative);
        AID id = new AID();
        id.setName(Id);
        try {
            aclMessage.setContentObject(msg);
        } catch (IOException e) {
            e.printStackTrace();
        }
        aclMessage.addReceiver(id);
        send(aclMessage);
    }
}
```

Listing 3.1: LeMAgent class

In the JADE framework, tasks that agents do are called *behaviours* JADE 2019. JADE provides three primary *behaviours*: *One-shot*, *Cyclic* and *Generic*. *One-Shot behaviours*, as the name implies, are used for tasks which occur in only once. *Cyclic behaviours* are used for operations keep occurring over time. Lastly *Generic behaviours* should be used when the execution of the task is dependent on the state of some condition. Furthermore JADE behaviours can be extended to model more complex tasks when needed. The JADE framework provides two complex *behaviours*: *WakerBehaviour* and *TickerBehaviour*. The *WakerBehaviour* provides a way to model a delayed task. It is possible to define an amount of time that needs to pass from the moment the *WakerBehaviour* is called to the moment it actually starts to executed. In the case of the *TickerBehaviour* it is possible to define an amount of time and the *TickerBehaviour* executes repeatedly a defined in time interval.

One thing that is common to all agents of the LeM model is they need to be able to answer to messages. This requirement is fulfilled by a *Cyclic behaviour* that waits for a message, processes it when it is received, and goes back to waiting or processing the next message if it was already received. When it comes to processing the Message the initial steps are also common to all agents. The implementation of common task is shown in Listing 3.1

In the implementation of agents, the necessary JADE *behaviours* and the actual business task that the agent needs to perform, were separated. This way the code related to the JADE framework and the simulation model can be separated. Each kind of agent has an interface that defines what the simulation model needs to implement. With this separation of concerns other agent models can be easily implemented and tested in the future.

The agents are very similar, containing only the necessary JADE *behaviours* to enable the market sequence model shown in Figure 3.4. All three types of agents have a *setup()* method that executes when the agents is created and can receive parameters. Each agents receives by parameter its correspondent agent model, which must implement the specified interface, *ISensor*, *IParticipant* or *IMIM*. Each agent also adds a *CyclicMessageRecive behaviour* to receive messages and overrides the *processLeMessage()* method to process the message according with the correct agent model.

```
public class ParticipantAgent extends LeMAgent {
    private IParticipant participant;

    @Override
    protected void setup() {
        Object[] args = getArguments();
        participant = (IParticipant) args[0];
        participant.registerParticipantAgent(this);
        addBehaviour(cyclicMessageReceive());
    }

    @Override
    protected void processLeMessage(LeMMessage lemMessage) {
        lemMessage.process(participant);
    }

}
```

Listing 3.2: ParticipantAgent class

```
public class SensorAgent extends LeMAgent {
    private ISensor sensor;

    @Override
    protected void setup() {
        Object[] args = getArguments();
        sensor = (ISensor) args[0];
        sensor.registerSensorAgent(this);
        addBehaviour(cyclicMessageReceive());
    }

    @Override
    protected void processLeMessage(LeMMessage lemMessage) {
        lemMessage.process(sensor);
    }
}
```

Listing 3.3: SensorAgent class

The *ParticipantAgent* and the *SensorAgent* classes, as shown in Listing 3.2 and Listing 3.3 differ on the interface used. As for the *MIMAgent* shown in Listing 3.4, it also includes another *behaviour*, a *OneShotBehaviour* used to launch the first market negotiation period.

```java
public class MIMAgent extends LeMAgent {
    private IMIM mim;

    @Override
    protected void setup() {
        Object[] args = getArguments();
        mim = (IMIM) args[0];
        mim.registerMIMAgent(this);
        addBehaviour(cyclicMessageReceive());
        addBehaviour(
                new OneShotBehaviour() {
                    @Override
                    public void action() {
                        mim.startNewMarketIteration();
                    }
                });
    }

    @Override
    protected void processLeMessage(LeMMessage lemMessage) {
        lemMessage.process(mim);
    }
}
```

Listing 3.4: MIMAgent class

Figure 3.5 presents a simplified model diagram of the LeM. The *LeMSimulation* is the class that is used to configure a simulation by defining the agents and their inputs. The *AgentBehaviours* classes contain the necessary JADE Behaviours, mostly for the concerns of message trading. The *Interfaces* define which methods each type of agent must implement in order to properly work in the LeM simulation. Lastly the *AgentModels* implement their respective agent interface, and thus define how each agent behaves in the simulation, while remaining compatible with it. The advantage of this approach is that different implementations for each agent can be used in the same simulation, for example *Participants* with different negotiation tactics or *sensors* with different kinds of reports.

3.3.2 Communication Mechanism

Two of the major points in MAS are the ability for agents to communicate and the possibility for distributed and concurrent execution of operations. In this specific simulation the process needs to work in both a concurrent and distributed environment. That is, messages can be sent in a concurrent way but the market negotiation period needs to be synchronous.

The communication and synchronization mechanisms developed for this simulation take inspiration from the negotiation model proposed by João Carneiro et al. 2019. In João Carneiro et al. 2019 the authors proposed a MAS model for Group Decision Making where each agent represents a person participating in the decision and an additional agent called *Facilitator*. The *Facilitator* acts as a mediator, in a similar way the MIM agent acts in the LeM. The synchronization algorithm 3.1 provides a simple way for a given agent to wait for a known number of expected messages and checking every time a new message is received before continuing its execution.

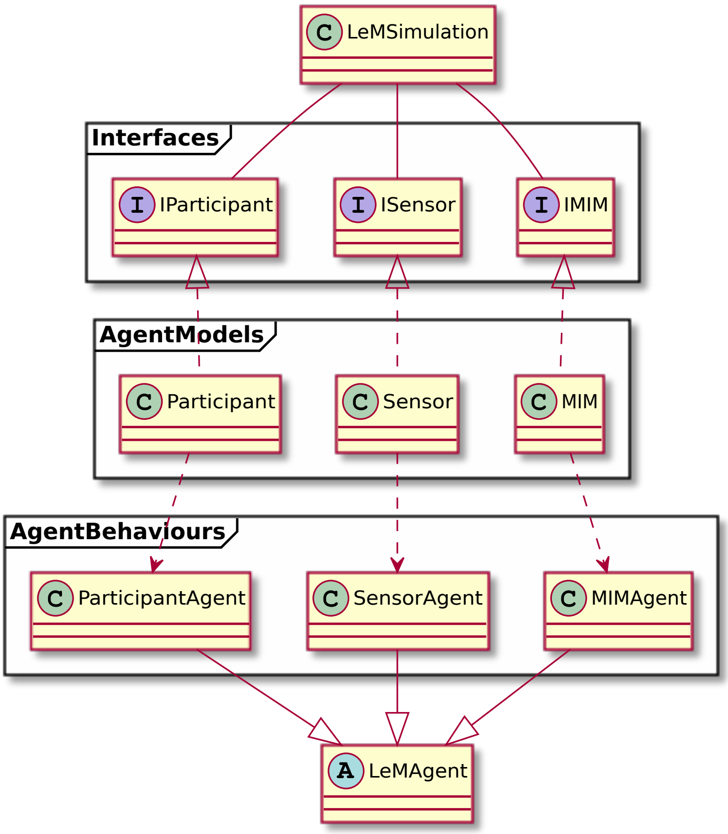

Figure 3.5: LeM Model Diagram

Algorithm 3.1 Synchronization algorithm

```
Input: Integer number of expectedMessages, msgListSize, msgList and newMsg
Output: Synchronization of the simulation

procedure ProcessReceivedMessage(expectedMessages, msgListSize, msgList, newMsg)
    msgList.add(newMsg)
    msgListSize++
    if expectedMessages == msgListSize then
        msgListSize = 0
        continueIteration()                ▷ Continue processing negotiation period
    else
        keepWait()                         ▷ Wait for more messages
    end if
end procedure
```

In the developed simulation this algorithm 3.1 is used to synchronize the MIM with the participants, and each participant with his respective sensor agents. The MIM needs this synchronization to ensure that it has received the proposals from all participants before processing the current market negotiation period and initiating the next. As for the participants the synchronization mechanism is necessary in order to ensure that the participant receives the data from all the sensors before evaluating its energy needs and making its proposal for the current market negotiation period.

One of the architectural decisions taken in the development was the separation of concerns into two different parts, which are message exchanging and the logic to process said messages. By doing so the development process is divided into simpler steps, and it is possible to abstract the domain logic in an interface for each agent. This way it is possible to implement different ways of processing the messages while keeping the same message exchanging base. This abstraction is possible due to the way messages are treated in the system.

JADE exchanges ACLMessages, this a is a class that can identify the sender and receiver of messages as well as provide a payload for the actual content that the agent desires to send. Once again abstraction was used, the LeMMessage is an interface that all messages exchanged by LeMAgent must follow. This way exchanging messages can be seen as having an external message *ACLMessage* used for message delivering purposes and an internal message *LeMMessage* which is carried inside *ACLMessage* to deliver the information. In this implementation the *LeMMessage* is being carried as a serialized Java object. It could also be carried serialized as JSON, XML or other format if necessary, as long as the agents agree on the structure of the messages. One advantage in a distributed environment and with a format such as JSON, for example, is that messages can easily be encrypted which is within the security concerns described in Section 2.6.1.

There are four kinds of messages used in the simulation, all implementing the *LeMMessage* base message. These kinds of messages are:

- *CallForProposal* - sent by the MIM to the Participants to request proposals for the market negotiation period;
- *CallForReading* - sent by the Participants to his Sensors to request updated values;
- *SensorReading* - sent by the Sensors to answer the *CallForReading* sent by the Participant;
- *Proposal* - sent by the Participant to answer the *CallForProposal* sent by the MIM.

The *CallForProposal* and *CallForReading* messages do not have any additional information, their message type is enough to identify everything necessary. In the case of the *SensorReading* and the *Proposal* additional information is needed.

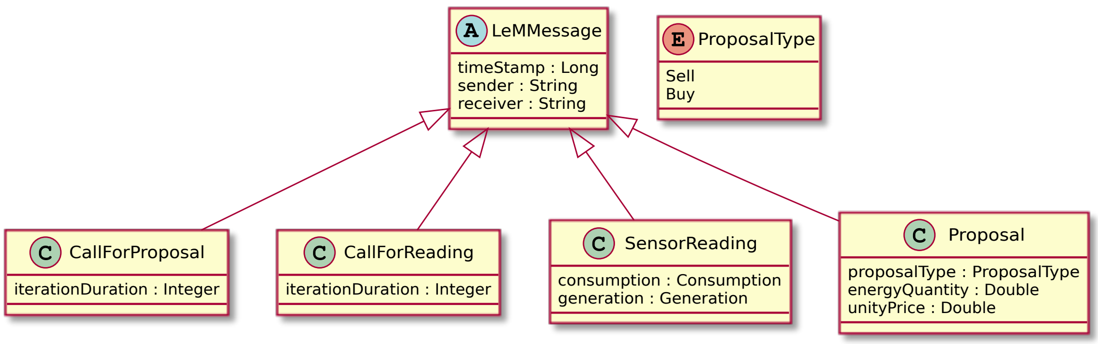

Figure 3.6: Message Model Diagram

3.3.3 Simulation input and database

An integral part for this simulation model for the LeM is the possibility to use realistic data. Realistic data is data based or construed with a real background. In this study the input data used is based on datasets with consumption and generation form real buildings and is presented in Section 4.3.

To make use of this data however it is necessary to create methods to read and to consult the input data. Achieving a fast and flexible way to access and consult the input data was an objective so that the simulation is not bottlenecked by the data. In order to meet these objective the decision was to create a database to where the input data is loaded before the start of the simulation and can be queried using the Structured Query Language (SQL). Another decision that concerns the input data is the structure that the data needs to have to be loaded to the database. The input structure must be easy to work with and able to contain all the necessary information. The data to be loaded here is consumption and generation values, more specifically the amount of energy consumed or generated in periodic intervals. The structure defined to model this data is a table that matches the beginning of the period when the data was consumed, that is date and time, and amount of energy. This structure is exemplified in Table 3.1.

Table 3.1: Input structure example

Date	**Time**	**Energy**
00/11/2222	00:01	1
00/11/2222	00:02	2
00/11/2222	00:03	3

The presented input structure is simple and contains the necessary information, there is however a possible problem with formats. Date formats, time formats and even the unit of measure for energy can vary across datasets. To create a more versatile input structure a second header row containing expression to represent the date, the time and the energy unity, as is shown is Table 3.2. Different expressions from the ones shown in Table 3.2 are also possible, for example: *dd/MM/yyyy* or *yyyy/MM/dd* for Date, *HH-mm-ss* or *HH:mm* for Time, and *kwh* for Energy.

Table 3.2: Input structure with formats

Date	**Time**	**Energy**
dd-MM-yyyy	HH:mm:ss	wh
02-07-2014	00:00:00	199,1843886
02-07-2014	00:01:00	149,4661368
02-07-2014	00:02:00	182,3250437

The database used was the PostgreSQL database *PostgreSQL* n.d. This is a free and open-source relational database, available for all major operating systems and more than capable for the needs of this project. To create the database the Object-Relational Mapping (ORM) approach was chosen. The ORM approach is based on creating the database tables from the code classes. This methodology allows for faster development by abstracting some of the database concerns for the programmer and for this reason was chosen.

With the data available for the simulation there will be only two kinds of sensors, generation and consumption. The generation, consumption and sensor models are shown in Figure 3.7. The Figure shows the relation between the models, where each *Generation* or *Consumption*

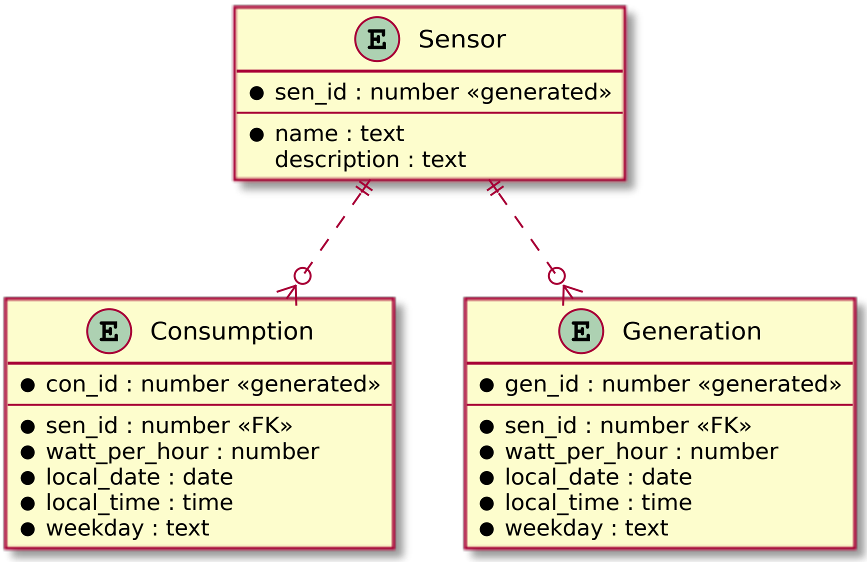

Figure 3.7: Database Data Model Diagram

entry is related to only one *Sensor*, and the *Sensor* is related to many *Generation* or *Consumption* values. The *Sensor* contains: a key *ID*, a text field *name* and an optional text field *description*. The *Generation* and *Consumption* both contain: a key *ID* and a foreign key *sensor-ID*, a number field *watt_per_hour*, a date field *local_date*, a time field *local_time* and text field *weekday*.

```
public static void insertData(Object obj) {
  EntityTransaction tx = entityManager.getTransaction();
  tx.begin();
  try {
    entityManager.persist(obj);
    tx.commit();
  } catch (Exception e) {
    logger.error("cannot commit transaction", e);
    tx.rollback();
  }
}

public static void batchInsertData(List entities) {
  int i = 0;
  int batchSize = 1000;
  for (Object e : entities) {
    entityManager.persist(e);
    i++;
    if (i % batchSize == 0) {
      EntityTransaction tx = entityManager.getTransaction();
      tx.begin();
      entityManager.flush();
      entityManager.clear();
      tx.commit();
    }
  }
}
```

Listing 3.5: Insert queries

The ORM approach allows the possibility to create queries directly on the java code in a very simple way. Listing 3.5 shows the possibilities for inserting data in the database, there is a single Object insert and a batch insert option. As for selecting data, Listing 3.6 shows the queries to select data from the database. The queries are the *findPrevDaysForForecast* used to select values from the specified sensor and before the specified date and time, the *findNextValue* used to select a single value from the specified sensor and immediately after specified date and time, and lastly the *findValuesByDate* used to select values from the specified sensor and between the specified dates and times. The data queries shown in Listing 3.6 are only for *Consumption*, but the same is possible for *Sensor* and *Generation*.

```java
public static List<Consumption> findPrevDaysForForecast(String sensor,
    LocalDateTime currentDate) {
  return entityManager
      .createQuery("FROM Consumption " +
          "AS c " +
          "WHERE sensor.name = :sensor " +
          "AND c.date < :currentDate " +
          "AND c.weekday = :weekday " +
          "ORDER BY  c.date DESC"
      ).setMaxResults(MIM.trainDaysForForecast)
      .setParameter("sensor", sensor)
      .setParameter("currentDate", currentDate)
      .setParameter("weekday", currentDate.getDayOfWeek().name())
      .getResultList();
}
public static Consumption findNextValue(String sensor, LocalDateTime
    currentDate) {
  List<Consumption> val = entityManager
      .createQuery("FROM Consumption " +
          "AS c " +
          "WHERE sensor.name = :sensor " +
          "AND c.date > :currentDate " +
          "ORDER BY  c.date ASC "
      ).setMaxResults(1)
      .setParameter("sensor", sensor)
      .setParameter("currentDate", currentDate)
      .getResultList();
  if (val.isEmpty()) {return null;}
  return val.get(0);
}
public static List<Consumption> findValuesByDate(String sensor,
    LocalDateTime start, LocalDateTime end) {
  return entityManager
      .createQuery("FROM Consumption " +
          "AS c " +
          "WHERE sensor.name = :sensor " +
          "AND c.date BETWEEN :startDate AND :endDate ")
      .setParameter("sensor", sensor)
      .setParameter("startDate", start)
      .setParameter("endDate", end)
      .getResultList();
}
```

Listing 3.6: Select queries

3.4 Trust Model

The objective for the Trust Model is to, at any point in time, be able to attribute a Trust value to any participant. That is a numeric value that represents how trustworthy or not the system considers a given participant.

The ReGreT model Sabater and Sierra 2005 appears to be a very complete model. As expressed by Sabater and Sierra 2005 individual trust models, as is the case of ReGreT, are ideal for scenarios with a small or medium number of participants, as is expected for a LeM. However, since Participant Agents will not communicate directly with each other it may not be possible to obtain witness information as used in the social dimension of ReGreT. Furthermore, depending on the legislation participants may not have the right to access to each other data, thus making a model such as ReGreT unusable in this scenario.

For these reasons, it is proposed an Institutional Pinyol and Sabater-Mir 2013 approach where a central institution, in this case the MIM, is responsible for ensuring the trust within the LeM. Before presenting the proposed trust formulation some considerations are presented about the Portuguese Legislation that is relevant for the scenario.

3.4.1 Legislation Considerations

According to the *Article 9 no. 8 & 9 - Lei da Defesa do Consumidor - Lei no. 47/2014* 2014, the Government should take measures to protect the interests of consumers, as well as to prevent them from being harmed with regard to matters of electricity supply.

In addition, *Article 7 - Lei da Defesa do Consumidor - Lei no. 47/2014* 2014 provides that consumers have the right to information, in this case they have the right of being informed about the service *Article 8 no. 1 - Lei da Defesa do Consumidor - Lei no. 47/2014* 2014; as well as the right to quality of said service *Article 4 - Lei da Defesa do Consumidor - Lei no. 47/2014* 2014. The central market entity must be able to guarantee this quality. The service will be provided indirectly by participants (producers and prosumers) who intend to sell the energy on the market. Thus, the central market entity should have access to the data of these participants, in order to ensure that the service they are going to provide has the desired quality.

The central market entity, in turn, by enabling the sale of energy, is also providing a service. Thus, this central entity has a duty to guarantee the quality of its service to every participant, including producers and prosumers.

In order to have this quality assurance, central market entity needs to make sure that no other participant is manipulating the market price.

Therefore, it may also be necessary for regular consumers to make their data available to ensure that the market is reliable and trusted in both directions of the negotiation.

The lack of information from any participant could lead to a decrease in trust levels in the market. The right to information is constitutionally provided for *Article 37 - Constituição da República Portuguesa - Lei no. 1/2005* 2005 and is also specifically regulated by *Article 7 - Lei da Defesa do Consumidor - Lei no. 47/2014* 2014 as well as non-compliance with the duty to inform *Article 8 no. 2, 4 & 5 - Lei da Defesa do Consumidor - Lei no. 47/2014* 2014.

With this approach, there is no need for the data to be made publicly available, but only made available from the participant to the central entity. This data, in turn, will be used to provide quality assurance to all market participants without having to disclose their information.

3.4.2 Trust Mechanism

To support the market it is proposed an Institutional based Trust model to be used by the MIM, capable of evaluating the behavior of participants and detecting faulty or malicious activities. As previously discussed such an approach is in accordance with the legislation and for this reason it is seen as having potential to be applied in a real LeM scenario.

The idea for the Trust mechanism is that with information such as weather, historical consumption and generation data, and other contextual data, it is possible to use forecasting methods to try to predict what the participant's consumption, generation or proposals should be in the current market negotiation period. The proposed Trust mechanism is based on using such forecasted values to obtain an idea if the participant is trustworthy over time. Since forecasting methods always have a certain degree of uncertainty a single proposed value that does not match the forecasted value does not provide a reliable metric. So by using an evaluation over time it is thought that incorrect forecasted values become negligible. Figure 3.8 shows a diagram of the Trust evaluation process. As shown the trust evaluation process takes three values as input: the participant's proposed values for the current market negotiation period, the participant's trust value from the previous negotiation period, and the forecasted value based on the participants historical and contextual data.

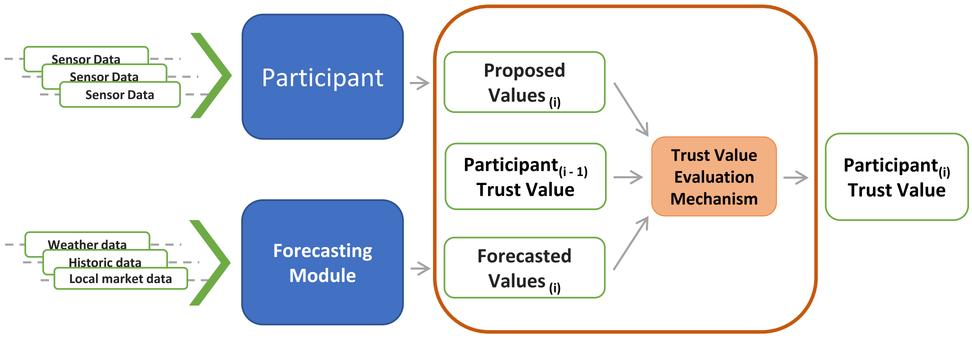

Figure 3.8: Trust Evaluation Process

The Trust Value ranges from $[0, 1]$ where 1 is the highest trust and 0 lowest trust value. The Trust value for a participant p in negotiation period i is represented as t_{pi}.

The evaluation formula takes several variables into consideration that can be configured to obtain the best possible results, these variables are:

- ar represents the *acceptance range* which is a percentage value;
- tiv represents the *trust increase value* a value by which the participant's trust is increased;
- tdv represents the *trust decrease value* a values by which the participant's trust is decreased;
- sv_{pi} represents the *submitted value* by participant p in market negotiation period i;
- fv_{pi} represents the *forecasted value* for participant p in negotiation period i;

- and lastly t_{p0} represents the *default trust value* the trust value with which all participants start with.

In case a participant has several data values that can be analyzed for trust, n values, the trust evaluation is performed for all for individual and them result is averaged. Equation 3.1 shows how the trust evaluation is calculated by being combined with either the Equation 3.2 for the asymmetric acceptance range or the Equation 3.3 for the symmetric acceptance range.

The difference between the asymmetric and the symmetric acceptance range is that the asymmetric has a higher acceptance range when the forecasting mechanism over estimates the value, since a percentage from a higher value results in a higher range.

$$t_{pi} = t_{p(i-1)} + \frac{1}{n}\sum_{i=1}^{n} trust\_eval(sv_{pi}, fv_{pi}) \tag{3.1}$$

$$trust\_eval\_asym(sv_{pi}, fv_{pi}) = \begin{cases} tiv & \text{if } sv_{pi} > fv_{pi} * (1 - ar) \text{ AND } sv_{pi} < fv_{pi} * (1 + ar) \\ tdv & \text{otherwise} \end{cases} \tag{3.2}$$

$$trust\_eval\_sym(sv_{pi}, fv_{pi}) = \begin{cases} tiv & \text{if } fv_{pi} > sv_{pi} * (1 - ar) \text{ AND } fv_{pi} < sv_{pi} * (1 + ar) \\ tdv & \text{otherwise} \end{cases} \tag{3.3}$$

The proposed trust evaluation mechanism is further presented in Algorithm 3.2. A java implementation of the algorithm was made following this pseudo-code structure.

Finally, there needs to be some consideration of how each participant's trust value is interpreted. Two things need to be taken into account: a participant that always submits real and true values should be fully trustworthy and so should be evaluated with a 1.0 trust value, on the other hand a participant that always submits false values should not be trusted and should have a trust evaluation of 0.0.

There is however some subjectivity in considering these trust evaluations. For examples, a participant that always submits real and true values and is evaluated with a 0.9 trust value, or a participant that always submits false values and is evaluated with a 0.1 trust value also seem like accepted evaluations. Given this subjective nature of the trust evaluation three trust ranges are proposed.

The first is the *Trustworthy* range where the trust value is $[h_t, 1]$, and any participant in this rage is fully trusted. The second range is *Unsure* range where the trust value is $[m_t, h_t[$, and any participant in this rage is considered to be a possible malicious or faulty participant and should, for example be further evaluated by the market authority. Lastly there is the *Untrustworthy* range where the trust value is $[0, m_t[$, and any participant in this range is considered a malicious or faulty participant and should be prevented from participating in the market. The values of, h_t minimum threshold for high trust and m_t minimum threshold for medium trust, are variable values that can be configured accordingly to the needs of the LeM.

Algorithm 3.2 Trust evaluation algorithm

Input: Double: ar, tiv, tdv, sv_{pi}, fv_{pi}, t_{pi-1}, Boolean: $isAsymmetric$
Output: t_{pi}

procedure evaluateTrust(ar, tiv, tdv, sv_{pi}, fv_{pi}, t_{p0})
    $t_{pi} = t_{pi-1} +$ evaluationFromForecasting(ar, tiv, tdv, sv_{pi}, fv_{pi}, t_{p0})
    if $t_{pi} > 1.0$ **then**
        $t_{pi} = 1.0$
    end if
    if $t_{pi} < 0.0$ **then**
        $t_{pi} = 0.0$
    end if
end procedure

procedure evaluationFromForecasting(ar, tiv, tdv, sv_{pi}, fv_{pi}, t_{p0})
    if realValueMatchForecast(ar, sv_{pi}, fv_{pi}) **then**
        return tiv
    else
        return tdv
    end if
end procedure

procedure realValueMatchForecast(ar, sv_{pi}, fv_{pi})
    if $isAsymmetric$ **then**
        return asymetric(ar, sv_{pi}, fv_{pi})
    else
        return symetric(ar, sv_{pi}, fv_{pi})
    end if
end procedure

procedure asymetric(ar, sv_{pi}, fv_{pi})
    $min = fv_{pi} * (1.0 - ar)$
    $min = fv_{pi} * (1.0 + ar)$
    return $max > sv_{pi} \&\& min < sv_{pi}$
end procedure

procedure symetric(ar, sv_{pi}, fv_{pi})
    $min = sv_{pi} * (1.0 - ar)$
    $min = sv_{pi} * (1.0 + ar)$
    return $max > fv_{pi} \&\& min < fv_{pi}$
end procedure

3.5 Overview

This chapter introduced the design and development of the solution. First, some considerations regarding the problem were made. Then, the proposed MAS to model and simulate LeM was described. The entire implementation process was also described. And finally, the proposed trust mechanism was presented, based on some legal considerations.

The solution presented here will be evaluated in the experimentation and evaluation process described in the next chapter.

Chapter 4

Experimentation and Evaluation

This chapter presents the considerations related with the simulation, experimentation scenarios and the evaluation of the proposed solution, as well as the results obtained in the experimentation. Section 4.1 delineates the research hypotheses. Section 4.2 presents the evaluation metrics. The case study and evaluation methodology is described in Section 4.3. Section 4.4 presents the study results and discussion. And finally, Section 4.5 presents an overview of the chapter.

4.1 Hypotheses

To properly validate the work carried out in this dissertation some research hypotheses were considered and proposed. Each hypothesis considers the objectives of this work and will give a way of validation. The hypotheses proposed are the following:

1. Using the proposed trust methodology it is possible to dynamically update the trust value of a participant;
2. The MIM agent is able to use the proposed trust methodology to access the trust value of a participant;
3. The performance of forecasting methods has a direct impact on the trust evaluation;
4. A well performing forecasting method supports a good trust evaluation;
5. The higher the amount of false values a participant submits the lower its trust value will be.

4.2 Evaluation Metrics

To validate any scientific work a well defined metric is always an important aspect, and this thesis is no exception. The performance of the trust formulation needs to be measured with a well defined metric, and in this case the trust value is exactly the metric needed for this situation. If the trust value given by the trust formulation is dynamically adjusted in the right direction, positively or negatively, then the trust formulation is seen as a viable option, if this does not happen then the trust formulation is seen as non viable option.

Furthermore, the proposed trust methodology, in Section 3.4.2, includes trust ranges designed to facilitate the processes of interpreting the trust value. These ranges can also be used as a metric by analyzing if the participant's trust value is being updated to fall in the expected range. To use these ranges it is first necessary to define the values for the variables

h_t minimum threshold for high trust and m_t minimum threshold for medium trust. In the following case study these variables take the values of $h_t = 0.8$ and $m_t = 0.5$. This being the case the trust ranges are: *Trustworthy* $[0.8, 1]$, *Unsure* $[0.5, 0.8[$ and *Untrustworthy* $[0, 0.5[$. With these ranges defined it is possible to define a simulation scenario with participants that have an expected trust range and evaluate how the proposed trust methodology performs.

4.3 Case Study and Methodologies

Simulation scenarios or case studies can provide important information about the behavior of participants in the system, which parts of the system work as expected and what unexpected problems might occur. To obtain valuable information however it is necessary to perform simulations with realistic and relevant scenarios. These simulation scenarios should take into consideration the context of the problem and the hypotheses that are being considered. Such a simulation can help to understand the system as a whole and might show particularities of the system and of the proposed LeM trust methodology that had not been thought of before. These simulations will be performed various times in order to obtain a large set of results data. Finally, to validate the hypotheses proposed in this thesis the results will be evaluated considering the metrics described in Section 4.2.

The idea for these case study is centered on understanding how the trust mechanism proposed behaves with different estimated forecasting methods and with participants who have different biases in their proposals. To achieve this it is also considered the necessity to use realistic data.

The methodology used for this simulation has two key aspects. The first one is to configure participants that vary in the amount and intensity of false proposals. And the second one is modeling forecasting methods as a Normal Standard Distribution based on what the real proposal value should be, this way forecasting methods with distinct levels of accuracy and precision can be estimated.

The data used in the simulations performed, is realistic consumption data available in *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d. The market was simulated for a 24 hours period and with 15 minutes market negotiation period duration, which results in a total of 96 market negotiation periods. Each simulation was performed 10 times and its results were averaged. The 24 hours simulated were of a Monday, simulated from hour 00:00 to hour 24:00.

Each simulation was performed with 10 participants, each one having his own bias in the proposals sent:

1. **TP** - True Proposer: Is the only who does not have a bias and always sends the real value;
2. **LUP** - Low Under Proposer: Sends a real value 80% of the times and a value between 20% to 30% under the real value the rest of the times;
3. **MUP** - Medium Under Proposer: Sends a real value 50% of the times and a value between 40% to 60% under the real value the rest of the times;
4. **HUP** - High Under Proposer: Sends a real value 30% of the times and a value between 70% to 90% under the real value the rest of the times;

5. **LOP** - Low Over Proposer: Sends a real value 80% of the times and a value between 20% to 30% over the real value the rest of the times;
6. **MOP** - Medium Over Proposer: Sends a real value 50% of the times and a value between 40% to 60% over the real value the rest of the times;
7. **HOP** - High Over Proposer: Sends a real value 30% of the times and a value between 70% to 90% over the real value the rest of the times;
8. **LUaUP** - Low Under and Over Proposer: Sends a real value 80% of the times and a value between 30% under to 30% over the real value the rest of the times;
9. **MUaOP** - Medium Under and Over Proposer: Sends a real value 50% of the times and a value between 60% under to 60% over the real value the rest of the times;
10. **HUaOP** - High Under and Over Proposer: Sends a real value 30% of the times and a value between 90% under to 90% over the real value the rest of the times.

The reasoning for these participants configurations are that, the True Proposer acts as a base line showing if the trustworthy participants are being correctly identified. Then there are three kinds of bias: under, over, and under and over, and each happening with different levels of frequency and intensity, from low, to medium to high. The idea here is that from low to high the trust level should be decreasing. Also considering the trust ranges previous defined the idea is that the TP participant should be on the *Trustworthy* range, the LUP, LOP, and LUaOP participants should be on the *Unsure* range, and the other participants should all be in the *Untrustworthy* range.

The data source used by each participant was the following:

1. **TP** - Private Home 1 Canizes et al. 2015; *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2011 June 03 to 2011 June 17, and using the day 06-06-2011 for the simulation;
2. **LUP** - Private Home 2 Canizes et al. 2015; *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2012 July 16 to 2012 July 26, and using the day 16-07-2012 for the simulation;
3. **MUP** - Private Home 3 Canizes et al. 2015; *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2013 January 23 to 2013 February 07, and using the day 28-01-2013 for the simulation;
4. **HUP** - Private Home 4 Canizes et al. 2015; *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2014 January 06 to January 06 30, and using the day 06-01-2014 for the simulation;
5. **LOP** - Private Home 1 Canizes et al. 2015; *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2011 June 03 to 2011 June 17, and using the day 06-06-2011 for the simulation;
6. **MOP** - Private Home 6 *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2011 December 25 to 2011 December 15, and using the day 26-12-2011 for the simulation;
7. **HOP** - Private Home 7 *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2011 September 26 to 2011 October 03, and using the day 26-09-2011 for the simulation;

8. **LUaUP** - Private Home 8 *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2012 June 01 to 2012 June 15, and using the day 04-06-2012 for the simulation;
9. **MUaOP** - Private Home 9 *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2012 December 29 to 2013 January 12, and using the day 31-12-2012 for the simulation;
10. **HUaOP** - Private Home 10 Fernandes et al. 2013; *Open Data Sets « IEEE PES Intelligent Systems Subcommittee* n.d., containing data from 2012 June 01 to 2012 June 30, and using the day 04-06-2012 for the simulation.

As it is shown participant TP and LOP are using exactly the same source data, this however is not a problem for the simulation, as it only means that their consumption was the same for that day and should not affect the results.

As for the estimated forecasting methods, they were configured in a similar way to the participants configuration. Seven estimator methods were simulated, in decreasing leaves of accuracy and precision. The estimated forecasting methods have the following mean $\bar{x}$ and standard deviation σ. The estimated methods $\bar{x}$ and σ values used were the following:

- **Perfect Predictor** - $\bar{x} = 1.0$ $\sigma = 0.0$;
- **Low Center Predictor** - $\bar{x} = 1.0$ $\sigma = 0.2$;
- **Low Under Predictor** - $\bar{x} = 0.9$ $\sigma = 0.2$;
- **Low Over Predictor** - $\bar{x} = 1.1$ $\sigma = 0.2$;
- **High Center Predictor** - $\bar{x} = 1.0$ $\sigma = 0.4$;
- **High Under Predictor** - $\bar{x} = 0.8$ $\sigma = 0.4$;
- **High Over Predictor** - $\bar{x} = 1.2$ $\sigma = 0.4$.

Each estimated forecasting was used with the Symmetric and Asymmetric acceptance method. The naming convention for the estimated forecasting methods is Low or High to identify the standard deviation used and Center, Under or Over for the mean used. With the exception of the Perfect Predictor, that is here to model a forecasting method that always outputs the correct value and provides a baseline comparison for the other estimator methods.

The last point for the configuration is the values used in the variables of the *Acceptance Range* ar, *Trust Increase Value* tiv, *Trust Decrease Value* tdv and the *Initial Trust Value* t_{p0}. The values used were $ar = 0.5$, $tiv = 0.01$, $tdv = -0.08$ and $t_{p0} = 0.8$.

4.4 Case Study Results and Discussion

To compare the results of the different estimated forecasting methods the trust values were plotted, showing the evolution of the trust value for each participant over time, through line chart graphs. To show these results in a clear way, each simulation was divided into 3 graphs, separated into UP, OP and UaOP participants and the TP participant is included in all 3 graphs to provide a point of comparison.

Looking at Figure 4.1 there is a clear distinction between the UP participants and the OP and UaOP. UP participants were evaluated with higher trust values. Even the HUP participant

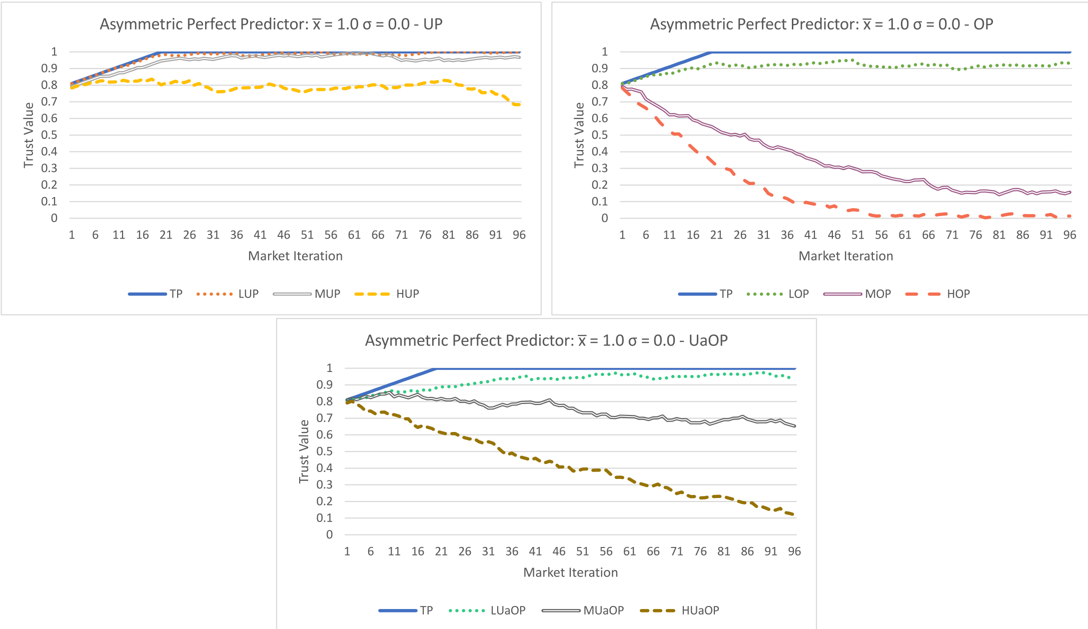

Figure 4.1: Asymmetric Perfect Predictor

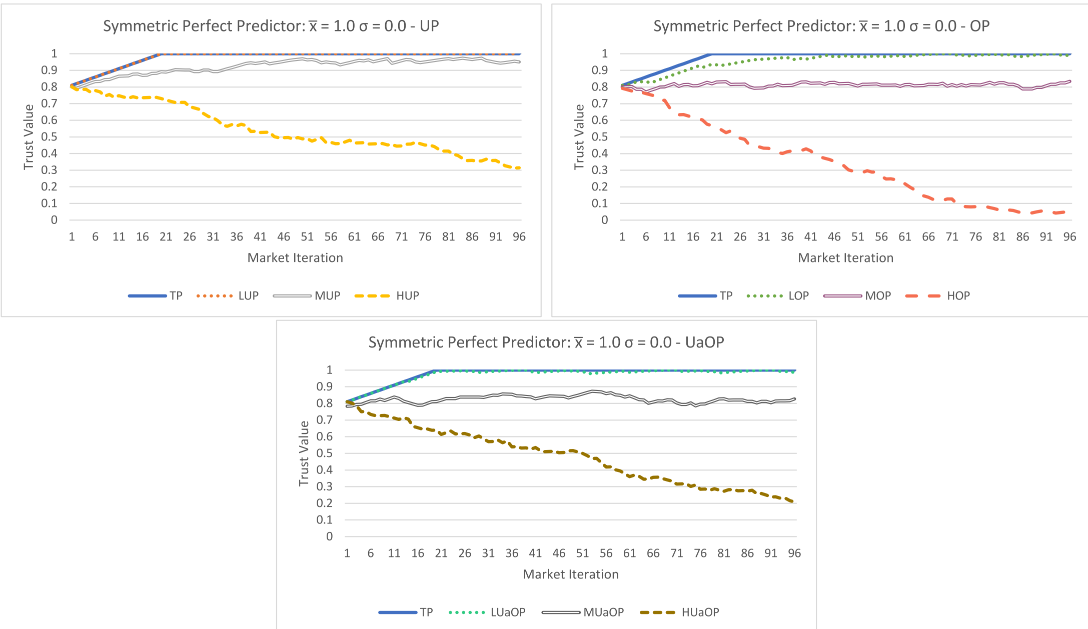

Figure 4.2: Symmetric Perfect Predictor

obtained a very high trust value. Another aspect that is visible is that as participants send more false values their trust value decreases. Analyzing The Figure 4.2 the results have some changes from the Asymmetric model. In the case of UP participants there was a lower trust value for the HUP participant. On the other hand both the MOP and the MUaOP participants have higher trust values.

Starting with the Low Center estimated forecasting method, and happening with every other, is the fluctuation that appears in the TP participant's trust value. In the previous estimator the trust value for this participant was always 1.0, but now with the uncertainty in the

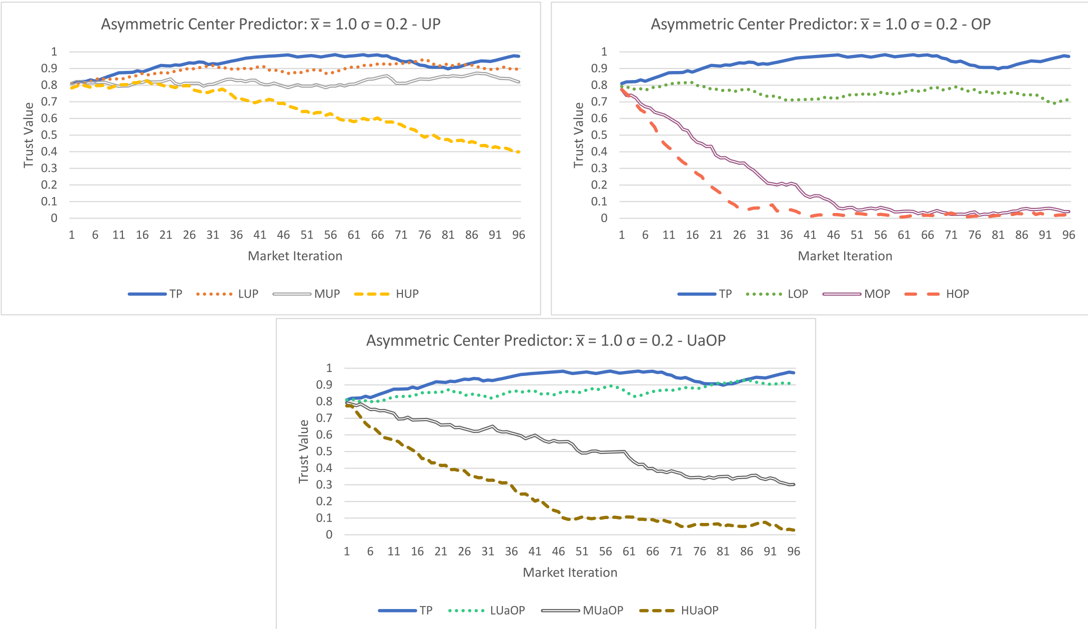

Figure 4.3: Asymmetric Low Center Predictor

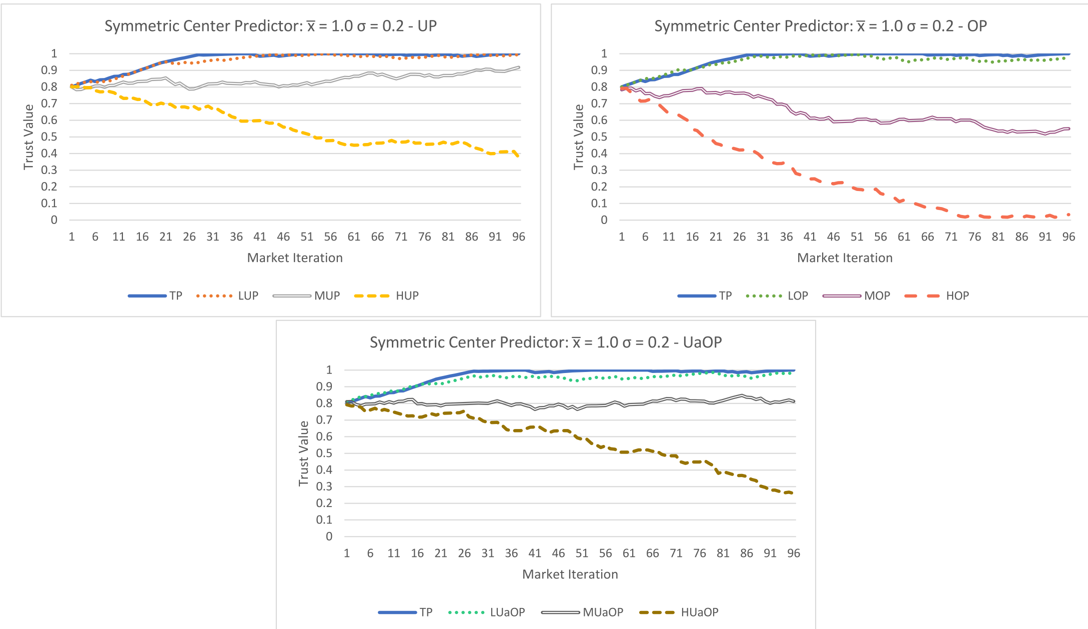

Figure 4.4: Symmetric Low Center Predictor

estimated forecasting method the trust value oscillates. Figure 4.3 shows the results for the Asymmetric Low Center which were similar to the Asymmetric Perfect Predictor but with trust values slightly bellow on all participants. As for Figure 4.4 it also shows results very similar to the Symmetric Perfect Predictor but with lower values on the medium participants, which is even an improvement in the classification.

Continuing with the analyzes we see in Figure 4.5 a clear drop in performance that is evidenced by the trust evaluation given to the TP participant. With this estimated forecasting method tendency towards under predicting values the acceptance range becomes smaller

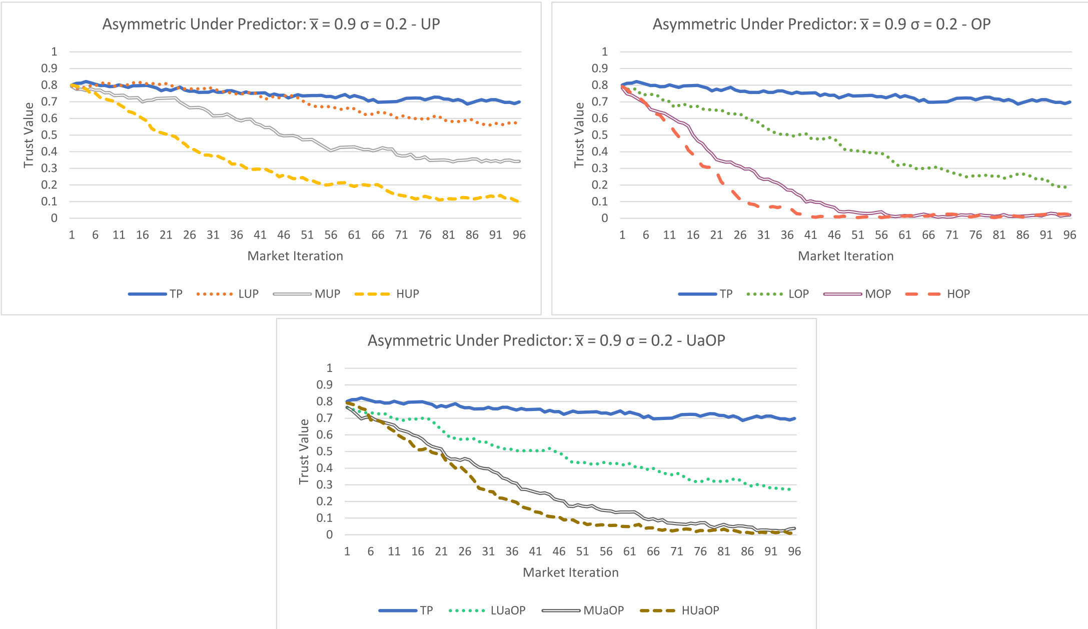

Figure 4.5: Asymmetric Low Under Predictor

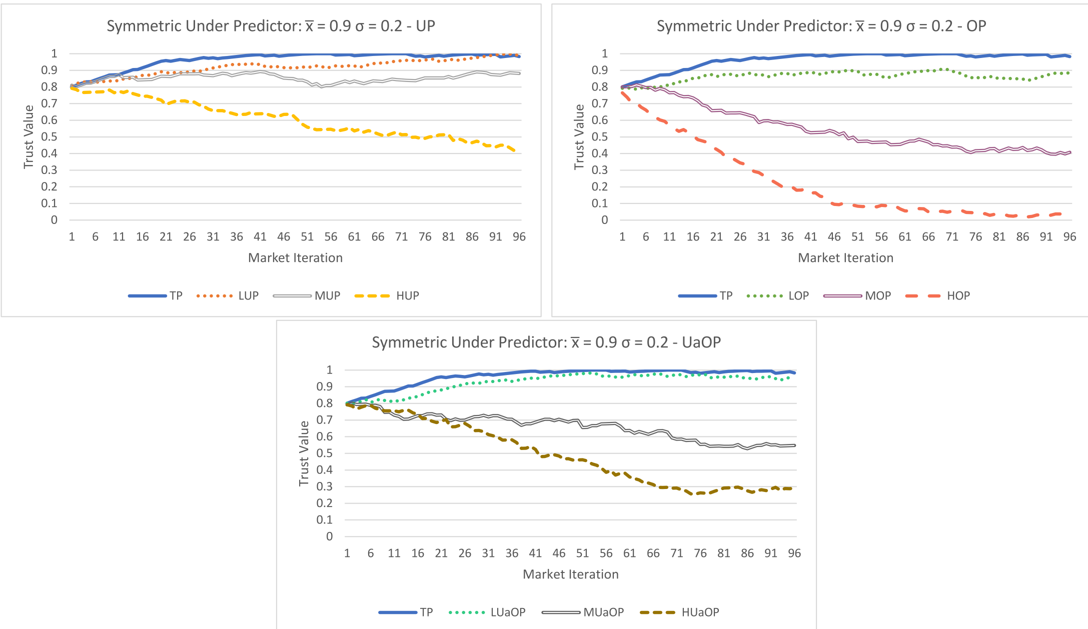

Figure 4.6: Symmetric Low Under Predictor

and more values are wrongly labeled as untrustworthy. This behavior however is corrected by using the Symmetric acceptance range, as shown in Figure 4.6 where the results are very similar to to the Symmetric Perfect Predictor shown in Figure 4.2.

The Low Over Predictor however does not show the differences seen in the previous estimator method. In both the Asymmetric Figure 4.7 and Symmetric Figure 4.8 scenarios the results are comparable to the respective Asymmetric and Symmetric Perfect Predictor estimator. This indicates that the Acceptance Range formulas are flexible enough to accommodate for some biases in the forecasting methods.

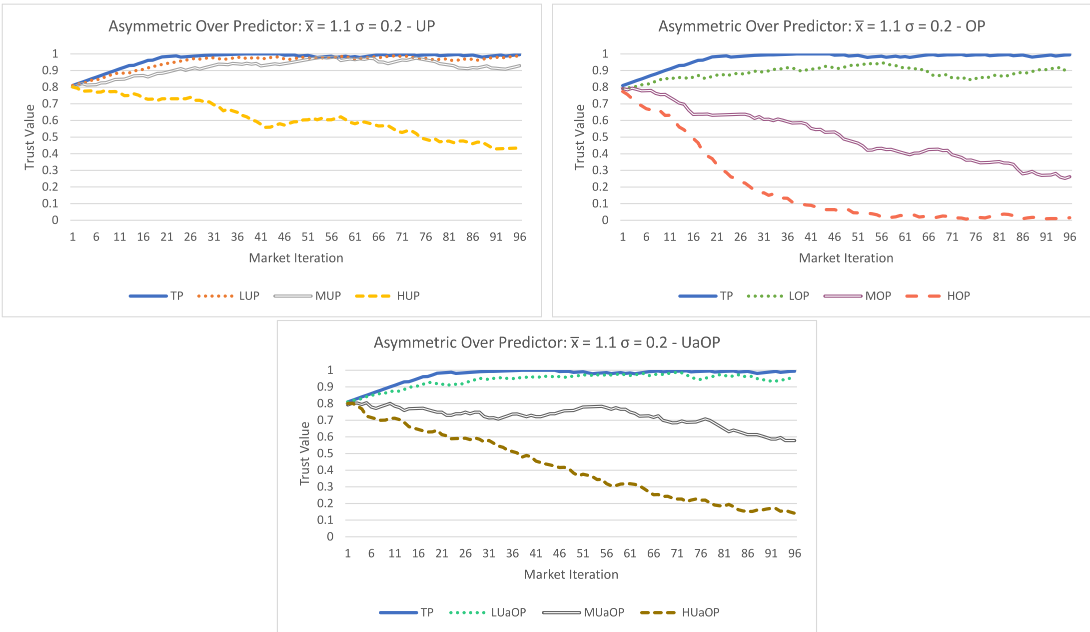

Figure 4.7: Asymmetric Low Over Predictor

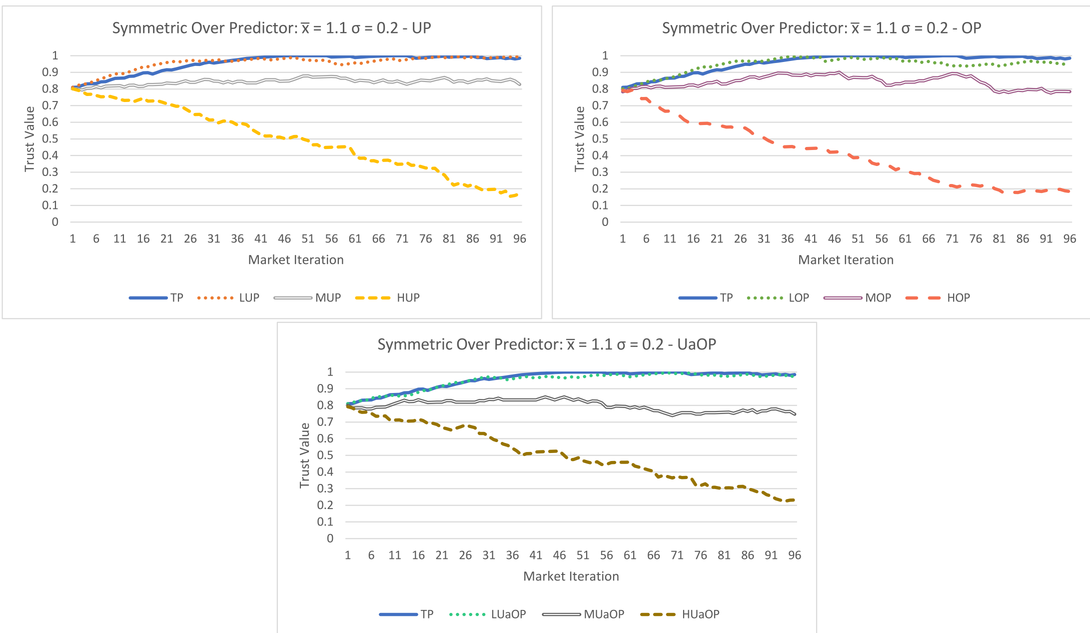

Figure 4.8: Symmetric Low Over Predictor

Until this point all estimated forecasting methods were similar in the final results and overall were able to correctly label the TP participant, this however does not happen with the High Predictors.

Looking at the High Center Predictor the results are very different from the previous estimated methods. Both the Asymmetric Figure 4.9 and Symmetric Figure 4.10 evaluated all participants with a low trust value, including the TP participant. The Asymmetric gave a slightly higher evaluation to the TP participant, but still very low to be desirable. The

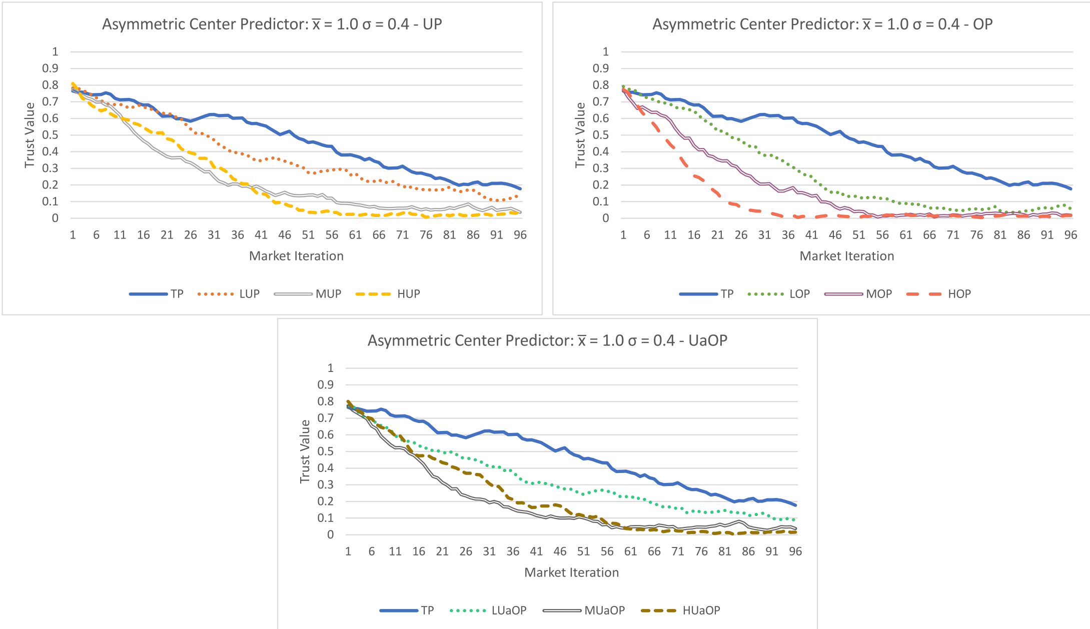

Figure 4.9: Asymmetric High Center Predictor

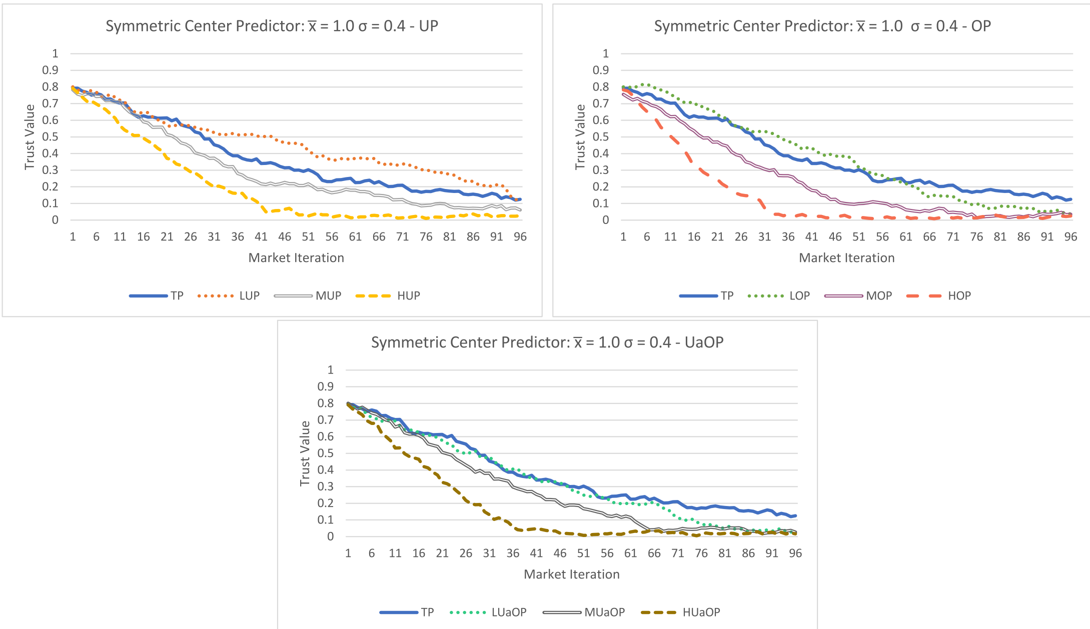

Figure 4.10: Symmetric High Center Predictor

fact that, with this estimated forecasting method, all participants were labeled as untrustworthy shows that is unsuitable for this task. This result indicates that, as proposed in the research hypothesis 3, the performance of forecasting methods has a direct impact on the trust evaluation.

The High Under Predictor obtained trust results even lower then the High Center Predictor. With this estimated forecasting method the differences between the Asymmetric Figure 4.11 and the Symmetric Figure 4.12 models are negligible. Once again the TP participant obtained a really low value, approximately 0.0, just like with the High Center Predictor, these

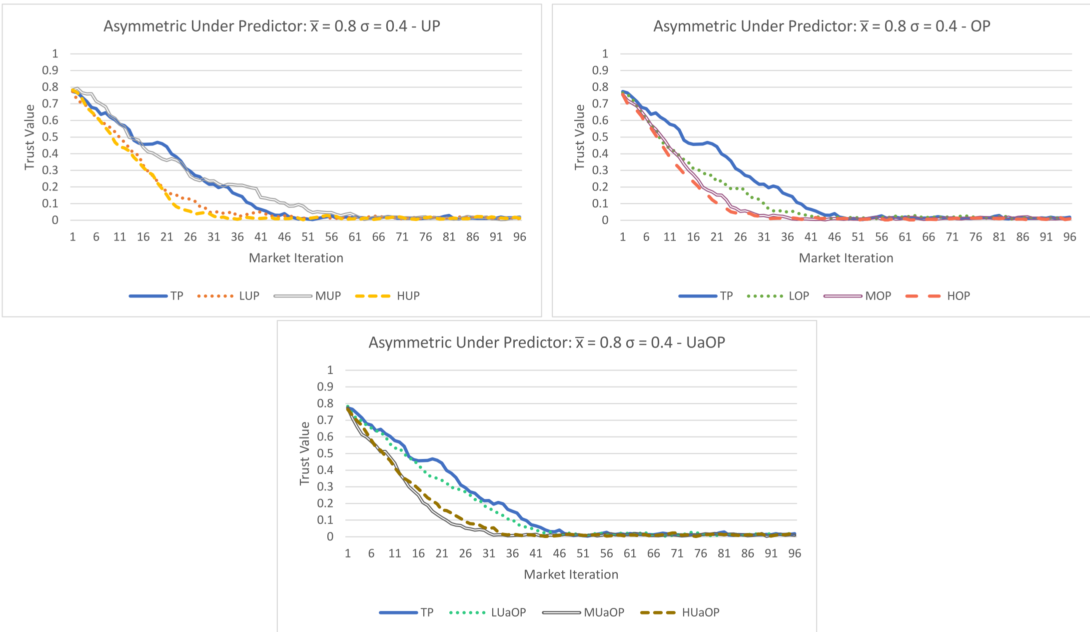

Figure 4.11: Asymmetric High Under Predictor

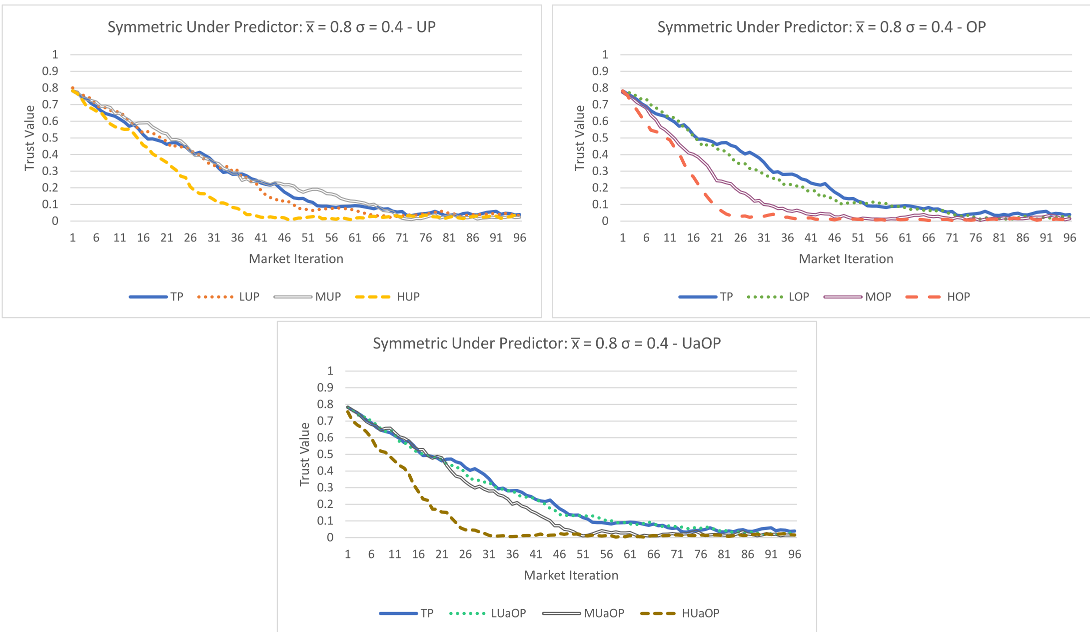

Figure 4.12: Symmetric High Under Predictor

results show that such a forecasting method is undesirable for a real application scenario.

The last of the estimated forecasting methods is the High Over Predictor. Contrary to the previous High Predictor this estimated method shows a very significant difference between the Asymmetric and the Symmetric models. The Asymmetric model Figure 4.13 showed better evaluations for all participants when compared to the Symmetric model Figure 4.14. This difference occurs due to the acceptance range being calculated from a higher value and, as such, accepting higher differences between the proposed values pv and the foretasted values fv. The trust evaluation with the Symmetric model Figure 4.14 is very similar to the

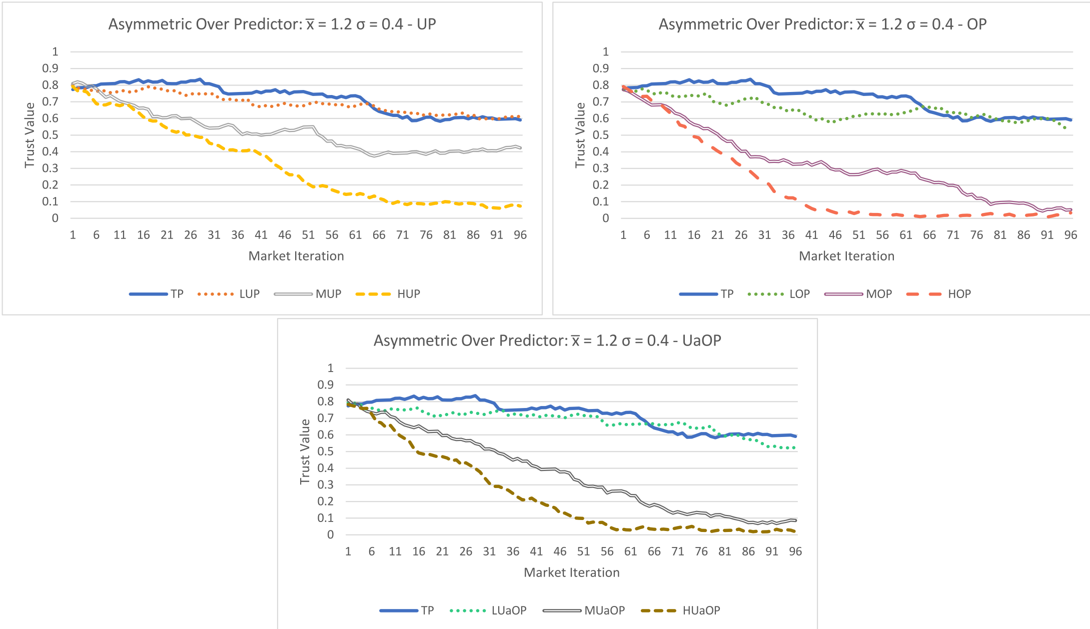

Figure 4.13: Asymmetric High Over Predictor

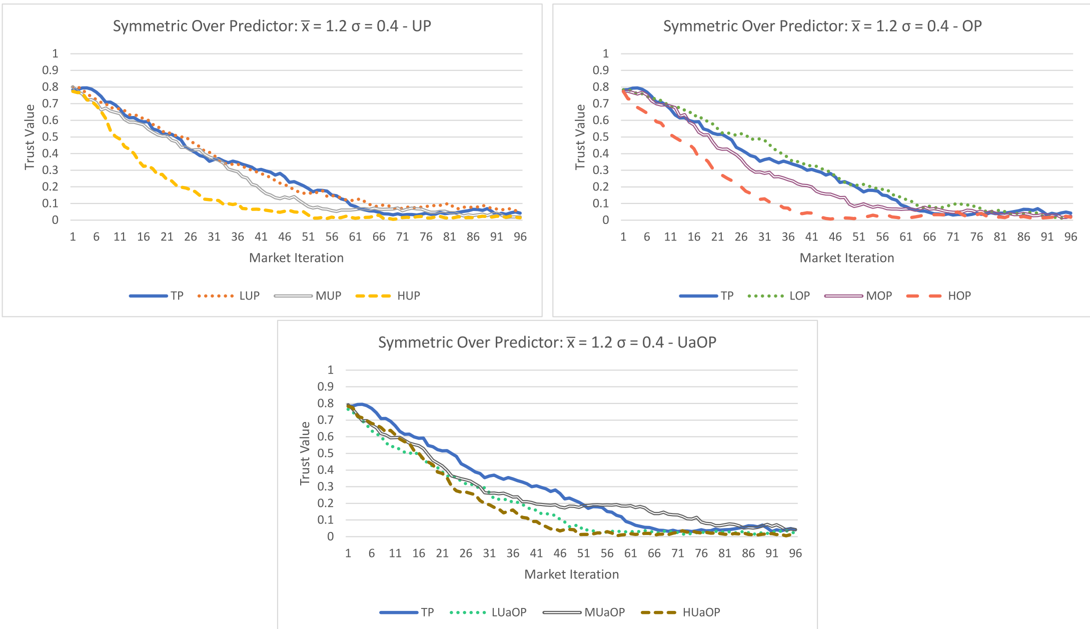

Figure 4.14: Symmetric High Over Predictor

other High predictors and once again is unusable for a real scenario. As for the Asymmetric model Figure 4.13 the low evaluation given to the TP participant, in the *Unsure* range, also makes it not the ideal forecasting method for a real application scenario, but it shows that choosing to use the Asymmetric or the Symmetric model is an important consideration and choosing the Acceptance model that better suits the forecasting method being used can have a big impact on how effective the trust model performs as a whole.

Looking at the data in a different way, as presented in Figure 4.15 one of the research hypotheses is confirmed. When looking at the values of trust from Low to Medium to High participants it is clear that the trust value decreases in each one. Thus confirming the idea that participants with a higher number of false proposals are correctly labeled with lower trust values.

Figure 4.15: Trust values by forecasting method

Table 4.1: Final trust values

	TP	LUP	MUP	HUP	LOP	MOP	HOP	LUaUP	MUaOP	HUaOP
A_P	**1**	0.999	0.967	0.683	0.932	**0.156**	**0.013**	0.95	0.653	**0.12**
S_P	**1**	1	0.951	**0.314**	0.986	0.834	**0.041**	0.988	0.827	**0.208**
A_LC	**0.973**	0.896	0.819	**0.399**	**0.712**	**0.04**	**0.027**	0.9	**0.302**	**0.028**
S_LC	**1**	0.994	0.918	**0.378**	0.976	0.55	**0.033**	0.976	0.812	**0.259**
A_LU	0.699	**0.567**	**0.342**	**0.098**	0.197	**0.02**	**0.023**	0.274	**0.038**	**0.016**
S_LU	**0.983**	0.993	0.881	**0.414**	0.887	**0.408**	**0.035**	0.961	0.547	**0.292**
A_LO	**0.995**	0.988	0.929	**0.434**	0.909	**0.262**	**0.016**	0.952	0.578	**0.141**
S_LO	**0.985**	0.994	0.828	**0.17**	0.946	0.784	**0.184**	0.967	0.747	**0.232**
A_HC	0.177	0.132	**0.036**	**0.038**	0.057	**0.019**	**0.017**	0.09	**0.037**	**0.016**
S_HC	0.125	0.117	**0.061**	**0.027**	0.037	**0.035**	**0.025**	0.033	**0.027**	**0.017**
A_HU	0.019	0.01	**0.017**	**0.011**	0.015	**0.01**	**0.008**	0.016	**0.009**	**0.006**
S_HU	0.039	0.035	**0.023**	**0.022**	0.026	**0.015**	**0.015**	0.033	**0.016**	**0.016**
A_HO	0.591	**0.612**	**0.423**	**0.073**	**0.542**	**0.052**	**0.033**	**0.527**	**0.086**	**0.019**
S_HO	0.042	0.047	**0.019**	**0.014**	0.021	**0.024**	**0.018**	0.023	**0.043**	**0.011**

Table 4.1 shows the last trust value for each participant and with each estimated forecasting method. The values that fall within the expected trust ranges were marked as bold. Several

aspects are clear by looking at the results in this way, which are:

- Both the A_P and the S_P failed in several participants, and in every case by giving a trust value too high. This indicates that perhaps the *ar* value used was too flexible for this particular forecasting method. In other words the more accurate and precise the forecasting method is, the lower the *ar* value used needs to be;
- Other interesting observation is that all High estimated forecasting methods have a lot of trust values within the correct range, specially the A_HO forecasting method, this however is a false identification of good performance, because in all High forecasting methods the TP participant was marked as *Unsure* or *Untrustworthy*. This is an undesired result since a method that marks all participants as *Untrustworthy* becomes useless in a real practical application;
- Furthermore looking at the HUP, HOP and HUaOP participants we see that they were correctly labeled with a low trust value on all but one estimated forecasting method, the A_P, this again reinforces the idea that participants with a higher number of false values receive lower trust evaluations.

Taking into consideration these results it is possible to obtain an idea of the capabilities of the proposed trust methodology and make a final analyses by reviewing the research hypotheses in Section 4.3.

1. Using the proposed trust methodology it is possible to dynamically update the trust value of a participant. - This hypothesis is validated. As shown by our results this method is able to dynamically update the trust values of participants;
2. The MIM agent is able to use the proposed trust methodology to access the trust value of a participant. - This hypothesis is validated. In this simulation the trust evaluation was performed by the MIM agent using the proposed trust methodology;
3. The performance of forecasting methods has a direct impact on the trust evaluation. - This hypothesis is validated. As the results showed in the graphs, showing trust over time, and in the Table 4.1 the worse estimated forecasting methods, A_C, S_C, A_U, S_U A_O and S_O, evaluate all participants with low trust values. Thus failing in the task of identifying *Trustworthy* and *Untrustworthy* participants. On the other hand the estimated forecasting methods with better performance were able to make a better distinction between participants;
4. A well performing forecasting method supports a good trust. - This hypothesis has to be rejected. This because as shown by the result with the perfect forecasting methods, A_P and S_P, in the Table 4.1 some participants obtain a final trust value higher than desired. This happened mostly on the participants with a Low and Medium amount of false submissions. The conclusion here is that the performance of the forecasting method is not the only important factor and acceptance formula also has an impact on the results;
5. The higher the amount of false values a participant submits the lower his trust value will be. - This hypothesis is validated. This happened in almost every case and with all estimated forecasting methods as is shown in Figure 4.15.

4.5 Overview

This chapter presented the experimentation made to evaluate the proposed solution. Several research hypotheses were proposed as a basis to evaluate the solution. There was also a consideration made in evaluation metrics, namely the trust value and the trust ranges of *trustworthy*, *unsure* and *untrustworthy*.

The case study was described in this chapter. The test scenarios were made using realistic consumption data publicly available. The methodology used modeled several participants with different bias towards submitting false proposals, and distinct estimated forecasting methods. This methodology allowed the realization of several simulations that showed how the trust mechanism performed in different contexts.

Lastly, the case study results were presented and discussed. When looking at these results we were able to make several conclusions. The approach used in the trust mechanism shows potential as it was able to dynamically update the participant's trust value.

The different estimated forecasting methods provided a clear indication that the performance of the forecasting method being used has a direct impact on how effective the trust mechanism is.

However, the results also indicate that the forecasting method is not the only aspect that can influence the effectiveness of the trust mechanism, and other aspects as the: the acceptance range ar, the trust increase value tiv, the trust decrease value tdv, and choosing the adequate trust model, *symmetric* or *asymmetric*, can also have a big impact on performance of the trust mechanism, and should be taken into consideration.

The following, and last, chapter of this dissertation presents the conclusions of this work, including the scientific outcomes and ideas for future work.

Chapter 5

Conclusions

This chapter presents the conclusions of this dissertation. Section 5.1 summarizes the work developed; the objectives of the work and the analysis made to the research hypotheses are highlighted. Section 5.2 presents the scientific contributions resulting from this work. Section 5.3 describes some ideas for future developments in this work and in the scope of project Secure interactions and trusted Participation in local Electricity Trading (SPET).

5.1 Summary and Conclusions

This dissertation was carried out under the SPET Research & Development (R&D) Project. The main goals of this project are the development of a Multi-Agent System (MAS) for simulation and modeling Local Energy Market (LeM). The project also aims to analyze the security and trust issues necessary for the success of this type of energy market. Within the scope of the SPET project this dissertation focused on the requirements to simulate and model the LeM as a MAS, and on ensuring trust the LeM negotiations.

To fulfill the objectives of this work, a MAS was proposed and developed. This MAS subdivides LeM into three types of entities, namely:(i) the Sensor Agent, (ii) the Participant Agent and (iii) the Market Interaction Manager (MIM) Agent, each with their own responsibilities, thus facilitating, the process of modeling the market. To give response to the needs of trust in the LeM, a formulation is also proposed to calculate a trust value for each participant based on the analysis of the participant's historical data, contextual data, such as weather data, and by using forecasting methods to predict the participants expected behavior. The trust value given to participants evolves over time and taking into consideration its market submissions to the LeM, the forecasting of those submissions and considering the disparity between those values.

A case study was carried out in which several simulations were made with 10 participants using realistic consumption data and with different biases towards submitting false values. Each simulation used a different estimated forecasting mechanism with distinct levels of accuracy and precision. Simulations were made for a 24 hours period and 15 minutes market negotiation period duration, which resulted in a total of 96 market negotiation periods. This case study aim was to evaluate the ability of the proposed trust formulation to respond to market needs by evaluating each participant with an appropriate trust value.

The realization of the case study made it possible to analyze the proposed research hypotheses and allowed us to conclude that: (i)The forecasting methodology used has a big impact on the performance of the trust formulation, but the acceptance formula also needs to be considered. (ii)A bad forecasting method, will provide a bad trust evaluation. (iii)The higher the amount of false values a participant submits the lower his trust value will be.

The main scientific contributions resulting for from this work are:

- The analysis of LeM and the types of negotiations;
- The analysis of security and trust in LeM;
- The design of a MAS architecture to model and simulate the Local Energy Market, that considers the cyber-physical systems beyond market participants;
- The implementation of the MAS over JADE platform;
- The formulation of a dynamic trust mechanism based on historical data, contextual data, such as weather data, and forecasting methods;
- The definition of configurable trust ranges to interpret the trust value;
- The elaboration and proposal of research hypothesis and test scenarios;
- The realization of a case study that simulates the test scenarios to evaluate how the trust formulation performs, showing its strengths and weakness, and allowing the evaluation of the proposed research hypothesis.

5.2 Outcomes of this work

The work done in this dissertation resulted in several scientific publications:

- "A MAS Simulation Model for Trusted Local Energy Markets" R. Andrade, Pinto, and Praça 2019. This was a poster presentation and participation in the 2019 19th Portuguese Conference on Artificial Intelligence, (EPIA). The work presented an overview of this dissertation;
- "Analysis and Simulation of Local Energy Markets," Praça et al. in press. This was an article and presentation in the 2019 16th International Conference on the European Energy Market, (EEM). The work focused on simulating LeM and the MAS model developed in this dissertation was proposed in the article;
- "A Multi-agent System Framework for Dialogue Games in the Group Decision-Making Context", J. Carneiro et al. (In Revision Process, Accepted with minor revisions). This was an article submitted and accepted with minor revisions in the Group Decision and Negotiation journal. In this work a framework was proposed to develop MAS for the Group Decision-Making Context, using and architecture and message trading mechanism very similar to the one presented in this dissertation.

5.3 Future Work

LeM are a possible answer to today's needs to deal with the unpredictability of Renewable Energy Sources (RES), as well as allowing greater flexibility for energy trading among participants who in the traditional market do not have this option.

This work focused on modeling the LeM and answering the trust issues in this context. It presents promising results, albeit with space for improvements in future research. In addition, the SPET project also covers other research areas necessary for the success of the Local Energy Market.

Some ideas for future development and exploration of the topic of this work are:

- The use of different acceptance methods, such as acceptance with a static value, fuzzy logic, or another acceptance method that provides better results;
- There is also a need to establish more concretely which trust values would be the most ideal to assign to participants with different behaviors;
- Furthermore, another point of research should be continuing the exploration of trust methods, and combining them with real forecasting methodologies, in order to understand how a trust system works as a whole;
- Finally, with regard to the SPET project, the need to explore and deepen system and communication security issues, such as the use of encryption mechanisms for message exchange, is emphasized.

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