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Ontologies for the interoperability of multi-agent electricity markets simulation platforms

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Ontologies for the interoperability of multi-agent electricity markets simulation platforms

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«A ti»

«It will take time,

and it’s going to cost you much more

than you could have ever imagined.

However the opposition, take not one step back.

When the dust clears,

and the battle is finally finished…

…you will truly smile

for the first time

in years.»

Unknown author

Abstract

Electricity markets worldwide are complex and dynamic environments with very particular characteristics. These are the result of electricity markets’ restructuring and evolution into regional and continental scales, along with the constant changes brought by the increasing necessity for an adequate integration of renewable energy sources.

The rising complexity and unpredictability in electricity markets has increased the need for the intervenient entities in foreseeing market behaviour. Market players and regulators are very interested in predicting the market’s behaviour. Market players need to understand the market behaviour and operation in order to maximize their profits, while market regulators need to test new rules and detect market inefficiencies before they are implemented. The growth of usage of simulation tools was driven by the need for understanding those mechanisms and how the involved players' interactions affect the markets' outcomes.

Multi-agent based software is particularly well fitted to analyse dynamic and adaptive systems with complex interactions among its constituents, such as electricity markets. Several modelling tools directed to the study of restructured wholesale electricity markets have emerged. Still, they have a common limitation: the lack of interoperability between the various systems to allow the exchange of information and knowledge, to test different market models and to allow market players from different systems to interact in common market environments.

This dissertation proposes the development and implementation of ontologies for semantic interoperability between multi-agent simulation platforms in the scope of electricity markets. The added value provided to these platforms is given by enabling them sharing their knowledge and market models with other agent societies, which provides the means for an actual improvement in current electricity markets studies and development. The proposed ontologies are implemented in MASCEM (Multi-Agent Simulator of Competitive Electricity Markets) and tested through the interaction between MASCEM agents and agents from other multi-agent based simulators. The implementation of the proposed ontologies has also required a complete restructuring of MASCEM’s architecture and multi-agent model, which is also presented in this dissertation.

The results achieved in the case studies allow identifying the advantages of the novel architecture of MASCEM, and most importantly, the added value of using the proposed ontologies. They facilitate the integration of independent multi-agent simulators, by providing a way for communications to be understood by heterogeneous agents from the various systems.

Keywords: Electricity Markets, Multi-agent Simulation, Ontologies, Semantic Interoperability

Resumo

Os mercados de energia elétrica são ambientes complexos e dinâmicos que possuem características particulares. Tais características são resultado da sua reestruturação e evolução a escalas regionais e, por vezes, até continentais. A crescente necessidade de adaptação dos mecanismos existentes para que possam fazer face à integração adequada de fontes de energia renováveis também contribui para a peculiaridade destes mercados.

A constante complexidade e imprevisibilidade nos mercados de eletricidade aumentou a necessidade das entidades neles intervenientes preverem o seu comportamento. Os reguladores precisam testar e detetar ineficiências nos algoritmos do mercado antes de serem implementados. Por outro lado, os agentes compradores e vendedores têm a necessidade de compreender o comportamento do mercado e o seu modo de operação, de modo a maximizarem os seus lucros ou minimizarem os seus custos. O crescimento do uso de ferramentas de simulação foi motivado pela necessidade de compreensão destes mecanismos e de como as interações entre as entidades intervenientes afetam os resultados dos mercados.

Software baseado em tecnologia multiagente é particularmente adequado para estudar e analisar sistemas dinâmicos e adaptativos com interações complexas entre os seus constituintes, tais como os mercados de energia elétrica. Diversas ferramentas de modelação direcionadas ao estudo dos mercados reestruturados da eletricidade foram surgindo, como por exemplo o MASCEM (Multi-Agent Simulator of Competitive Electricity Markets). No entanto, estas ferramentas de simulação partilham uma limitação comum: a falta de interoperabilidade entre os vários sistemas, que permita o intercâmbio de modelos e conhecimento, e ainda o teste e estudo de diferentes modelos de mercado.

O MASCEM é um simulador multiagente de mercados competitivos de energia elétrica, que tem vindo a ser desenvolvido desde 2003. Inclui os principais modelos de mercado e as principais entidades que nele participam, permitindo o estudo dos modelos e comportamento do mercado e de cada um dos respetivos participantes. No entanto, com as constantes atualizações que o MASCEM tem acomodado, o seu ambiente tornou-se excessivamente complexo, revelando a fragilidade da sua arquitetura e da plataforma de comunicação dos agentes. Deste modo, tornou-se essencial reestruturar o sistema por completo, definindo uma nova arquitetura, um novo modelo multiagente, o uso de mecanismos adequados para lidar com os requisitos de tempos de execução, e, para facilitar a interoperabilidade com sistemas externos, o uso de semântica nas mensagens trocadas entre os principais intervenientes do mercado.

Esta dissertação propõe, além da reestruturação completa da arquitetura e modelo multiagente do simulador MASCEM, o desenvolvimento e implementação de ontologias para a interoperabilidade semântica entre plataformas multiagente no âmbito dos mercados de energia elétrica. O valor acrescentado a estas ferramentas é dado através da partilha do seu conhecimento e modelos de mercado com outras sociedades de agentes, dispondo assim dos meios para uma efetiva melhoria nos estudos e desenvolvimento dos atuais mercados de eletricidade.

Os resultados obtidos nos casos de estudo permitem identificar a adequação da nova arquitetura do simulador MASCEM, bem como as vantagens do uso das ontologias propostas. O uso destas ontologias facilita a integração de simuladores multiagente independentes, disponibilizando um modo para a compreensão das mensagens trocadas entre os agentes de sistemas heterogéneos.

Palavras-chave: Interoperabilidade Semântica, Mercados de Energia Elétrica, Ontologias, Simulação Multiagente

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Acronyms and Nomenclature

List of Acronyms

2E	**E**fficiency/**E**ffectiveness
ACL	**A**gent **C**ommunication **L**anguage
ADM	***A****i****D****-E****M*** *Ontology*
AI	**A**rtificial **I**ntelligence
AiD-EM	**A**daptive **D**ecision support for **E**lectricity **M**arkets Negotiations
ALBidS	**A**daptive **L**earning strategic **Bid**ding **S**ystem
AMES	**A**gent-based **M**odelling of **E**lectricity **S**ystems
AMS	**A**gent **M**anagement **S**pecification
ANN	**A**rtificial **N**eural **N**etworks
CAISO	**CA**lifornia **I**ndependent **S**ystem **O**perator
CfP	**C**all **f**or **P**roposal
CFP	***C****all* ***F****or* ***P****roposal Ontology*
CSP	**C**urtailment **S**ervice **P**rovider
DAI	**D**istributed **A**rtificial **I**ntelligence
DAML	**D**ARPA **A**gent **M**arkup **L**anguage
DECON	**D**ecision Support for **E**nergy **CO**ntracts **N**egotiation
DF	**D**irectory **F**acilitator
DL	**D**escription **L**ogic
DG	**D**istributed **G**eneration
DR	**D**emand **R**esponse
DSO	**D**istribution **S**ystem **O**perator
EU	**E**uropean **U**nion

EM	**E**lectricity **M**arket(s)
EMCAS	**E**lectricity **M**arket **C**omplex **A**daptive **S**ystem
EMO	***E**lectricity **M**arkets **O**ntology*
EMR	***E**lectricity **M**arkets **R**esults **O**ntology*
EPEX	**E**uropean **P**ower **EX**change
EPSO	**E**volutionary **P**article **S**warm **O**ptimization
EPX	*EPEX **O**ntology*
EV	**E**lectric **V**ehicles
FCT	***F**undação para a **C**iência e a **T**ecnologia*
FIPA	**F**oundation for **I**ntelligent **P**hysical **A**gents
GAPEX	**G**enoa **A**rtificial **P**ower **EX**change
GECAD	Research **G**roup on Intelligent **E**ngineering and **C**omputing for **A**dvanced Innovation and **D**evelopment
GME	***G**estore dei **M**ercati **E**nergetici*
GoF	**G**ang **o**f **F**our
ICL	**I**nteragent **C**ommunication **L**anguage
IEEE	**I**nstitute of **E**lectrical and **E**lectronics **E**ngineers
IP	**I**nternet **P**rotocol
ISO	**I**ndependent **S**ystem **O**perator
JADE	**J**ava **A**gent **DE**velopment framework
KB	**K**nowledge **B**ase
KIF	**K**nowledge **I**nterchange **F**ormat
KQML	**K**nowledge **Q**uery and **M**anipulation **L**anguage
MAS	**M**ulti-**A**gent **S**ystem(s)
MASCEM	**M**ulti-**A**gent **S**imulator of **C**ompetitive **E**lectricity **M**arkets
MASGriP	**M**ulti-**A**gent **S**mart **Gri**d simulation **P**latform

MatLab	**Mat**rix **Lab**oratory
MBL	***MIB**E**L** Ontology*
MG	**M**icro **G**rid
MIB	**M**anagement **I**nformation **B**ase
MIBEL	***M**ercado **IB**érico de **El**etricidade*
MISO	**M**idwest **I**ndependent **S**ystem **O**perator
MVC	**M**odel-**V**iew-**C**ontroller
NPO	***N**ord **P**ool **O**ntology*
OA	**O**ntology **A**gent
OAA	**O**pen **A**gent **A**rchitecture
OMIE	***O**perador del **M**ercado **I**bérico de **E**nergía - Polo Español, S.A.*
OWL	**W**eb **O**ntology **L**anguage
PLC	**P**rogrammable **L**ogic **C**ontroller
Prolog	***Pro**grammation en **Log**ique*
RDF	**R**esource **D**escription **F**ramework
RES	**R**enewable **E**nergy **S**ources
RfS	**R**equest **f**or **S**upport
RLA	**R**einforcement **L**earning **A**lgorithm
RMA	**R**emote **A**gent **M**anagement
SEPIA	**S**imulator for **E**lectric **P**ower **I**ndustry **A**gents
SG	**S**mart **G**rid
SL	**S**emantic **L**anguage
SPARQL	SPARQL Protocol and RDF Query Language
SREMS	**S**hort-medium **R**un **E**lectricity **M**arket **S**imulator
SVM	**S**upport **V**ector **M**achines

SW	**S**ocial **W**elfare
US	**U**nited **S**tates of America
VPP	**V**irtual **P**ower **P**layer
XML	e**X**tensible **M**arkup **L**anguage

List of Nomenclature

$\top$	is a special concept with every individual as an instance
$\bot$	empty concept
$\sqcap$	intersection or conjunction of concepts
$\sqcup$	union or disjunction of concepts
$\exists$	existential restriction
$\sqsubseteq$	concept inclusion
$\equiv$	concept equivalence
R	atomic role (object property)
U	atomic role (data property)

1 Introduction

1.1 Motivation

The new challenges that the electricity markets (EM) restructuring produced has increased the importance of the EM operation study. The EM restructuring raised the complexity and competitiveness of the market, which, together with its unpredictable evolution, hardens the decision-making process [Meeus *et al.*, 2005].

Several models have emerged trying to overcome market challenges. Despite the guidance provided by some pioneer countries experience in what regards the implemented market models' performance, it is still premature to take definitive conclusions [Sioshansi, 2013]. Thereby, the use of tools that allow the study of different market mechanisms and the relationships between market entities becomes essential.

The need to understand these mechanisms and how the interactions between the involved players affects the outcome of the market has contributed to an increased use of simulation tools. Multi-agent based simulators are particularly well suited for the analysis of complex interactions in dynamic and complex systems such as the EM [Pinto *et al*., 2014b]. Simulators in this area must be able to deal with the dynamic and rapid evolution of EM and adopt the new models and constraints of the market, providing players with adequate tools to adapt themselves to this changing environment. Some of the main advantages that multi-agent approaches provide are the facilitated inclusion of new models, market mechanisms, player types, and different types of interactions [Santos *et al.*, 2015a]. In this domain some reference modelling tools have emerged, such as AMES (Agent-based Modelling of Electricity Systems) [Li and Tesfatsion, 2009], EMCAS (Electricity Market Complex Adaptive System) [Koritarov, 2004] and MASCEM [Praça *et al.*, 2003], [Santos *et al.*, 2015a].

Although several works have confirmed the adequate applicability of multi-agent simulation to the study of EM, they have a common limitation: the lack of interoperability between the various systems to allow the exchange of information and knowledge, to test different market models and to allow market players from different systems to interact in common market environments. Current tools are directed to the study of different EM mechanisms and to the analysis of the relationships between market entities, but they do not enable the interoperability with external systems.

These limitations point out the need for the interconnection between agent-based simulators in the scope of EM. These simulators could gain significant added value by sharing their knowledge and market models with other agent societies. Such tools would provide the means for an actual improvement in current EM studies and development.

1.2 Objectives

The development of agent-based simulation platforms is increasing as a good option in the simulation of real systems in which actors have different and often conflicting goals. These systems allow simulating different strategies and scenarios, providing their users with decision-support in accordance to their operating profiles. The use of multi-agent systems (MAS) in electric power systems is a reality, especially for the simulation of EM [Santos *et al.*, 2015a] and the simulation of the new paradigms, like smart grids and microgrids [Gomes *et al*., 2014a].

This work consists in the development of ontologies to enable the communication between distinct simulation platforms of EM, smart grids and microgrids. Domain ontologies should be defined for the existing GECAD simulation platforms – particularly AiD-EM (Adaptive Decision support for Electricity Markets Negotiations) [Pinto *et al*., 2015a] and MASGriP (Multi-Agent Smart Grid simulation Platform) [Gomes *et al*., 2014a], besides MASCEM – and for their interconnection, in order to enable the joint simulation of scenarios with different levels and types of markets. It is also intended that the ontologies allow the shared simulation between agent systems developed by external systems to GECAD. Additionally, in order to accommodate the required ontologies and facilitate the modularity and scalability of the multi-agent EM simulation platform, a restructuring process of this simulator's architecture and multi-agent model is also necessary.

In summary, this dissertation aims to:

- study the current trends and most promising solutions for the interoperability between different agent societies;
- develop domain ontologies for GECAD multi-agent simulation platforms, in the scope of power systems;
- develop and implement a general ontology, which enables the interoperability between GECAD multi-agent platforms and platforms developed by other research units;
- present the restructuring process required to provide the multi-agent EM simulation platform, MASCEM, with the means for agents' interoperability and greater flexibility;
- experiment and validate the developed and implemented solutions through realistic simulation scenarios, using real EM data, and considering the interoperability between MASCEM and other multi-agent systems.

1.3 Main contributions

In order to achieve the proposed objectives, it is essential to restructure MASCEM; particularly its communication platform. Given the existing limitations in MASCEM's old architecture, which made it difficult to update the existing models and to include new ones, and bearing in mind the goal of making MASCEM a FIPA (Foundation for Intelligent Physical Agents) compliant system, it has been decided to restructure the whole system.

With this restructuring, besides making MASCEM compliant with FIPA standards, new very relevant features, that are essential for the system, have also been developed, such as:

- the parallel execution of different simulation scenarios, which optimizes the time spent in studying different scenarios;
- automatic distribution of agents execution considering the characteristics of each available machine in the network and the resources needed for each agent;
- the easier inclusion and removal of market models due to its new modular architecture, which also enables the simulation of hybrid scenarios;
- a new output file format, automatically generated, taking into account the simulated data, including the characteristics and particularities of each type of agent present in the simulation, which facilitates the user analysis;
- the use of configuration files, making it a more flexible tool. When it is required to change any base configuration there is no need to change the code, but only the settings, *e.g.* for access to databases or access configuration to an external platform, such as AiD-EM or MASGriP, when the agents' interaction is required;
- the simplification of the agents' model, abstracting the concepts of each entity to avoid code replication wherever possible;
- the flexibility of execution according to the available time, allowing the user to decide the preference regarding the balance between the results quality and the execution time of the simulations.

However, the main contribution of this dissertation is the development of ontologies for the interoperability of multi-agent simulators in the scope of EM. There are inherent difficulties in the integration of independently developed agent-based systems, especially to access and map private ontologies. This work has the purpose of disseminating the development of interoperable multi-agent simulators in the EM research area, enabling knowledge exchange between them in order to take full advantage of their functionalities, and promoting the adoption of a common semantic that enables the communication between heterogeneous systems. For that purpose the *Electricity Markets Ontology* is proposed, a general ontology that gathers the main concepts of EM, so that it can be imported and extended by lower-level domain ontologies, facilitating mappings between them and the share of knowledge between systems. Domain specific ontologies for each market implemented in MASCEM are also proposed, as well as an ontology to enable the interoperability with AiD-EM, GECAD's decision support tool for EM negotiations, with MASGriP [Oliveira *et al.*, 2012] and with externally developed agents.

The proposed ontologies are public and are available online in MASCEM's website[1]. This way any Ontology Engineer or developer of multi-agent simulators of EM can easily have access to

[1] http://www.mascem.gecad.isep.ipp.pt/ontologies/

the proposed ontologies and incorporate them in their agents, hence being able to participate in joint simulations with MASCEM, AiD-EM and MASGriP.

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- FIGURE – Flexible and Intelligent Grids for Intensive Use of Renewable Energy Sources (PTDC/SEN-ENR/099844/2008);
- GID-MicroRede – Sistema de Gestão Inteligente e Descentralizado de Micro-redes de Distribuição Privadas, QREN, (Ref.34086);
- ID-MAP - Intelligent Decision Support for Electricity Market Players (PTDC/EEA-EEL/099832/2008);
- IMaDER – Gestão Inteligente de Recursos Energéticos Distribuídos a Curto Prazo em Ambiente Competitivo (PTDC/SEN-ENR/122174/2010);
- MAN-REM – Multi-agent Negotiation and Risk Management in Electricity Markets (PTDC/EEA-EEL/122988/2010);
- SASGER-MeC – Simulation and analysis of smart grids with renewable energy sources in the scope of competitive markets (NORTE-07-0162-FEDER-000101);
- SEAS – Smart Energy Aware Systems, (ITEA2 nº 12004, cluster EUREKA).

Additionally, throughout the development of this work, a total of twenty three scientific papers were published. Three scientific papers in SCI[2] indexed journals with high impact factor:

- Gabriel Santos, Tiago Pinto, Hugo Morais, Tiago M. Sousa, Ivo F. Pereira, Ricardo Fernandes, Isabel Praça, Zita Vale, *Multi-Agent Simulation of Competitive Electricity Markets: Autonomous systems cooperation for European Market modeling*, Energy Conversion and Management, vol. 99, pp. 387-399, July 2015, doi: 10.1016/j.enconman.2015.04.042, with impact factor of 4.380 in 2014;
- Hugo Morais, Tiago M. Sousa, Gabriel Santos, Tiago Pinto, Isabel Praça, Zita Vale, *Coalition of Distributed Generation Units to Virtual Power Players – A game theory approach*, Integrated Computer-Aided Engineering, vol. 22 no. 3, pp. 297-309, June 2015, doi: 10.3233/ICA-150490, with impact factor of 4.698 in 2014;
- Tiago Pinto, Zita Vale, Tiago M. Sousa, Isabel Praça, Gabriel Santos, Hugo Morais, *Adaptive learning in agents behaviour: A framework for electricity markets simulation*,

[2] Science Citation Index® (SCI®); http://thomsonreuters.com/products_services/science/science_products/a-z/science_citation_index/

Integrated Computer-Aided Engineering, vol. 21, no. 4, pp. 399-415, September 2014, doi: 10.3233/ICA-140477, with impact factor of 4.698 in 2014.

Five scientific papers in book chapters:

- Gabriel Santos, Tiago Pinto, Luís Gomes, Marco Silva, Hugo Morais, Zita Vale, Isabel Praça, *Agent-based Smart Grid Market Simulation with connection to real infrastructures*, The PAAMS Collection in Advances in Practical Applications of Heterogeneous Multi-Agent Systems, Advances in Intelligent Systems and Computing, vol. 8473, pp. 371-374, Y. Demazeau, *et al.*, Eds, Springer International Publishing, 2015;
- Tiago Pinto, Gabriel Santos, Luis Marques, Tiago M. Sousa, Isabel Praça, Zita Vale, Samuel L. Abreu, *Solar Intensity Characterization using Data-Mining to support Solar Forecasting*, 12th International Conference in Distributed Computing and Artificial Intelligence, Advances in Intelligent Systems and Computing, vol. 290, pp. 141-148, S. Omatu, *et al.*, Eds, Springer International Publishing, 2015;
- Ricardo Fernandes, Gabriel Santos, Isabel Praça, Tiago Pinto, Hugo Morais, Ivo F. Pereira, Zita Vale, *Elspot: Nord Pool Spot Integration in MASCEM Electricity Market Simulator*, The PAAMS Collection in Highlights of Practical Applications of Heterogeneous Multi-Agent Systems, Advances in Intelligent Systems and Computing, vol. 430, pp. 262-272, J. Corchado, *et al.*, Eds, Springer International Publishing, 2014, doi: 10.1007/978-3-319-07767-3_24;
- Tiago Pinto, Isabel Praça, Gabriel Santos, Zita Vale, *Demonstration of the Multi-Agent Simulator of Competitive Electricity Markets*, Advances on Practical Applications of Agents and Multi-Agent Systems, Vol. 7879, pp. 316-319, D. Hutchison, T. Kanade, J. Kittler, J.M. Kleinberg, F. Mattern, J.C. Mitchell, M. Naor, O. Nierstrasz, C.P. Rangan, B. Steffen, M. Sudan, D. Terzopoulos, D. Tygar, M. Vardi, G.Weikum, editors. Lecture Notes in Computer Science, Springer Berlin/Heidelberg, 2013, doi: 10.1007/978-3-642-38073-0_36;
- Gabriel Santos, Tiago Pinto, Zita Vale, Hugo Morais, Isabel Praça, *Upper Ontology for Multi-Agent Energy Systems' Applications*, Distributed Computing and Artificial Intelligence - Advances in Intelligent Systems and Computing, Vol. 217, pp. 617-624, S. Omatu, J. Neves, J.M. Corchado Rodriguez, J.F Paz Santana, S.R. Gonzalez (Eds), Springer Berlin Heidelberg, 2013, doi: 10.1007/978-3-319-00551-5_73.

And fifteen scientific papers in conferences of the research area:

- Gabriel Santos, Ricardo Fernandes, Tiago Pinto, Isabel Praça, Zita Vale, Hugo Morais, *MASCEM: EPEX SPOT Day-Ahead Market Integration and Simulation*, International Conference on Intelligent System Application to Power Systems 2015 - ISAP'15, Porto, Portugal, 11 – 16 September, 2015;
- Tiago Soares, Gabriel Santos, Tiago Pinto, Hugo Morais, Pierre Pinson, Zita Vale, *Analysis of Strategic Wind Power Participation in Energy Market using MASCEM simulator*,

International Conference on Intelligent System Application to Power Systems 2015 - ISAP'15, Porto, Portugal, 11 – 16 September, 2015;

- Tiago Pinto, Hugo Silva, Zita Vale, Gabriel Santos, Isabel Praça, *Pan-European Electricity Market Simulation considering the European Power Network capacities*, Fourth International Workshop on Artificial Intelligence Techniques for Power Systems and Energy Markets (IATEM 2015), Valencia, Spain, 1-4 September, 2015;
- Tiago Pinto, Marco Silva, Gabriel Santos, Luís Gomes, Bruno Canizes, Zita Vale, *Smart Grid and Electricity Market joint Simulation using complementary Multi-Agent platforms*, 2015 IEEE PowerTech, Eindhoven, Netherlands, 29 June - 2 July 2015;
- Francisco Silva, Brígida Teixeira, Tiago Pinto, Gabriel Santos, Isabel Praça, Zita Vale, *Demonstration of Realistic Multi-Agent Scenario Generator for Electricity Markets simulation*, 13th Conference on Practical Applications of Agents and Multi-Agent Systems PAAMS'15, Salamanca, Spain, 3th-5th June, 2015;
- Brígida Teixeira, Francisco Silva, Tiago Pinto, Isabel Praça, Gabriel Santos, Zita Vale, *Data Mining Approach to support the Generation of Realistic Scenarios for Multi-Agent simulation of Electricity Markets*, IA 2014 – Intelligent Agents (IA) at the IEEE SSCI 2014 (IEEE Symposium Series on Computational Intelligence), Orlando, Florida, USA, 09-12 December, 2014, doi: 10.1109/IA.2014.7009452;
- Tiago Pinto, Gabriel Santos, Zita Vale, Isabel Praça, Fernando Lopes, Hugo Algarvio, *Realistic Multi-Agent Simulation of Competitive Electricity Markets*, Third International Workshop on Intelligent Agent Technology, Power Systems and Energy Markets (IATEM 2014) at the 25th International Conference on Database and Expert Systems Applications (DEXA 2014), Munich, Germany, 01-05 September, 2014, doi: 10.1109/DEXA.2014.36;
- Fernando Lopes, Hugo Algarvio, Jorge A. M. Sousa, Hélder Coelho, Tiago Pinto, Gabriel Santos, Zita Vale, Isabel Praça, *Multi-agent Simulation of Bilateral Contracting in Competitive Electricity Markets*, Third International Workshop on Intelligent Agent Technology, Power Systems and Energy Markets (IATEM 2014) at the 25th International Conference on Database and Expert Systems Applications (DEXA 2014), Munich, Germany, 01-05 September, 2014, doi: 10.1109/DEXA.2014.40;
- Tiago Pinto, Gabriel Santos, Ivo F. Pereira, Ricardo Fernandes, Tiago M. Sousa, Isabel Praça, Zita Vale, Hugo Morais, *Towards a unified European electricity market: The contribution of data-mining to support realistic simulation studies*, 2014 IEEE PES General Meeting (GM), National Harbor, USA, 27 – 31 July, 2014, doi: 10.1109/PESGM.2014.6939565;
- Gabriel Santos, Tiago Pinto, Zita Vale, Hugo Morais, Isabel Praça, *MASCEM Restructuring: Ontologies For Scenarios Generation in Power Systems Simulators*, 2013 IEEE PES GM, Vancouver, British Columbia, Canada, 21-25 July 2013, doi: 10.1109/PESMG.2013.6672916;
- Tiago Soares, Gabriel Santos, Pedro Faria, Tiago Pinto, Zita Vale, Hugo Morais, *Integration in MASCEM of the Joint Dispatch of Energy and Reserves Provided by*

Generation and Demand Resources, ISAP 2013 - 17th International Conference on Intelligent System Applications to Power Systems, Toquio, Japan, 01-04 July, 2013;

- Gabriel Santos, Tiago Pinto, Zita Vale, Isabel Praça, Hugo Morais, *Virtual Power Players Internal Negotiation and Management in MASCEM*, ISAP 2013 - 17th International Conference on Intelligent System Applications to Power Systems, Tokyo, Japan 01-04 July, 2013;
- Catarina Ribeiro, Tiago Pinto, Hugo Morais, Zita Vale, Gabriel Santos, *Intelligent Remuneration and Tariffs for Virtual Power Players*, 2013 IEEE PowerTech Grenoble, Grenoble, France, 16-20 June, 2013, doi: 10.1109/PTC.2013.6652157;
- Gabriel Santos, Isabel Praça, Tiago Pinto, Sérgio Ramos, Zita Vale, *Scenarios Generation for Multi-Agent simulation of Electricity Markets based on Intelligent Data Analysis*, IEEE Symposium on Intelligent Agent (IA) at the IEEE SSCI 2013 (IEEE Symposium Series on Computational Intelligence), Singapore, 15-19 April, 2013, doi: 10.1109/IA.2013.6595183;
- Gabriel Santos, Tiago Pinto, Hugo Morais, Zita Vale, Isabel Praça, *Multi-Agent Simulation of Continental, Regional, and Micro Electricity Markets*, 23rd International Workshop on Database and Expert Systems Applications (DEXA 2012), Vienna, Austria, 03-06 September, 2012, Accession Number: WOS: 000312658400054.

Besides the mentioned papers, there is also a publication submitted to a SCI indexed journal that is under evaluation:

- Gabriel Santos, Tiago Pinto, Tiago M. Sousa, Isabel Praça, Hugo Morais, Zita Vale, *MASCEM: Optimizing the Performance of a Multi-Agent System*, IEEE Transactions on Industrial Informatics, Special Issue on Industrial Collaborative Networks.

These scientific contributions support the relevance of the developed work to the scientific community, in several fields, such as: artificial intelligence, ontologies, MAS, and intelligent power systems.

1.4 Document structure

This document is composed by five chapters. This first introductory chapter presented a brief description of the work developed, including its motivation, main goals, outline and main contributions, and the document structure.

Chapter 2 overviews the relevant background for the comprehension of this thesis. It starts by presenting an overview of EM restructuring process, including a discussion on its consequences and effects on the markets' participating entities, by describing its most common regulatory models. An introduction to agents and agent-based systems is provided, supporting its adequacy in the simulation of EM. Afterwards, the semantic for multi-agent interoperability is approached, highlighting the concepts of ontology and upper ontology, and the ontology service specification of FIPA. Finally, some multi-agent simulation tools are presented, describing MASCEM with particular detail, in addition to AiD-EM and MASGriP.

Chapter 3 presents the developed work. The chapter starts by describing MASCEM's restructuring, including its new architecture, multi-agent model and execution time optimization. Hereafter, the proposed ontologies developed in the context of semantic interoperability and their application in the multi-agent simulators are described.

Chapter 4 presents three case studies demonstrating the usefulness of the proposed ontologies in the interconnection between different MAS, as well as the advantages of the flexibility and optimization that have been made in the restructured simulator, by testing different scenarios representing different market circumstances, based on real EM data, conceived to demonstrate the proper functioning of the enhanced version of MASCEM, resulting from this work.

Finally, this thesis is concluded with Chapter 5, which presents the most important conclusions related to the developed work, its main achievements and some future work that might improve it.

2 Background

2.1 Introduction

The power sector business has been completely revolutionized by the emergence of liberalized EM. The sector's restructuring process brought out several challenges, requiring the transformation of the conceptual models that previously dominated the power sector [Sioshansi, 2013]. This restructuring made the market more competitive, but also more complex, posing new challenges to its participants. Therefore, the involved entities are forced to rethink their behaviour and market strategies.

To give entities decision support to address the new challenges, the use of simulation tools becomes decisive in order to study, analyse, and test different alternatives for markets' structure and evolution. For market participants it is important to anticipate scenarios and define strategies, while for the operators it is essential to test new market architectures. The main purpose of these tools is to deal with the constantly evolving reality of EM and grant actors with appropriate solutions to adapt themselves to the new reality, gaining experience to act in the context of a changing economic, financial, and regulatory environment. Market players aim to optimize their results (minimize costs if buying; or maximize profits if selling in the market) and operators must ensure a competitive and transparent market in which no entity has significant market power [Shahidehpour *et al.*, 2002].

After the introduction of EM, this chapter features the MAS theme, in order to properly discuss the advances of simulation based on this type of frameworks. Then, a discussion on semantics for MAS interoperability is provided, where the concepts of ontology and upper ontology are introduced, as well as the specification of FIPA's [FIPA, 2001] Ontology Service.

Additionally, a summary of the most relevant works developed in this scope is provided, supporting the potentialities that this type of technology presents in this area. It is presented an overview of the different tools that exist for the study and simulation of EM and a discussion of how MAS can be useful in this context.

Finally, a detailed description of MASCEM, which is the simulator restructured in the scope of this work, is also presented. Next steps have been also identified to allow the interoperability between systems, with the goal of enabling agents of a specific tool to participate in market simulations of other platforms, thus promoting the study of different markets and market types, taking advantage of the complementarities of different tools.

2.2 Electricity Markets

Over the last few decades, worldwide EM have been changing their paradigm due to EM restructuring. Some examples of the transformations applied are the deregulation of privately owned systems; and the privatization, liberalization and international integration of previously nationally owned systems [Shahidehpour *et al.*, 2002], [Sharma *et al.*, 2014].

Although nowadays EM operate in more complex and reliable models, they still present limitations, such as the exclusive participation of large players. Therefore, the increased use of distributed generation (DG), strongly based on renewable energy sources (RES) of intermittent nature, hardly contributes to the efficiency of the system, due to lack or excess of power generation. Furthermore, RES are still supported by governmental stimulus [Sioshansi, 2013].

Due to its restructuring, EM placed several challenges to governments and companies involved in the areas of generation, transmission and distribution of electrical energy. Dealing with these challenges has led to an increase of the competitiveness in this sector causing relevant changes and new difficulties and matters to be solved, such as the market operation rules, physical constraints of power systems and financial issues. In addition, nowadays a wide range of negotiation opportunities is available, turning the EM sector into a highly demanding and complex environment, through auction based markets, intraday and balancing negotiations, bilateral contracts, forwards and futures markets, among others [Meeus *et al.*, 2005].

This problem has been addressed in different ways throughout the world. Nevertheless, some common solutions are being embraced globally. EM are evolving to regional markets and some to continental scale. Transaction of huge amounts of electrical energy are already supported by EM, enabling the efficient use of renewable based generation in places where it exceeds the local needs [Sioshansi, 2013].

The European EM is a reference case of this evolution, where Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Great Britain, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland (via the SwePol Link), Portugal, Slovenia, Spain, Sweden and, most recently, Italy [PCR, 2015] have joined together into common market operator, resulting in joint regional EM [EMCC, 2015].

The United States (US) evidence is another example of the transformation of national EM into regional and continental EM. Midcontinent Independent System Operator (MISO) [MISO, 2014] and California Independent System Operator (CAISO) [CAISO, 2015] are examples of regional markets in US. Brazil has also integrated its regions into a joint EM [ONS, 2014]. Although not representing a continent as a whole, EM of Brazil and the US can be considered as continental EM due to their size.

As a result of the constant evolution of the EM environment, and the inclusion and change in the operation and players' participation in the market, it became imperative for professionals in the area to entirely understand the markets' principles and how to evaluate their investment under such a competitive environment. The shared interest of regulators and market players in foreseeing the market's behaviour required a clear understanding of EM principles, and the impact of power systems physics on market dynamics and vice-versa [Biggar and Hesamzadeh, 2014], [Meeus *et al.*, 2005]. Additionally, a suitable understanding of the diversity of market types and regulatory models that have been introduced is critical for the success of all involved players.

2.2.1 Regulatory models

The typical EM environment consists of a day-ahead pool (symmetric or asymmetric) where energy for the following day is negotiated. Typically, a floor for bilateral contracts is also considered [EAC, 2009]. Moreover, intraday markets are required to provide the means to renegotiate the previously traded power in order to meet the required adjustments towards the feasibility of the daily program and of the last scheduling [Santos *et al.*, 2012]. Given the different market opportunities, each market player must decide whether to, and how to, participate in each market type.

In addition to the trading entities, that try to buy or sell energy in the market, these markets also include the market and system operators. The market operator is the entity responsible for operating the market. It manages the pool by using a market-clearing tool which establishes the market price for each trading period and the accepted and refused bids. On the other hand, the system operator is the entity responsible for the management of the transmission grid and its technical constraints. After the establishment of a contract, the agreement is communicated to the system operator, which analyses its technical feasibility in the power system perspective; regardless of it being established through bilateral contracts or through the pool.

2.2.1.1 Day-ahead market

The day-ahead market [Klemperer, 1999], [Sheblé, 1999] (also known as spot market) is a daily basis market which aims at trading energy for each time period (usually an hour or half-hour) of the next day. It was designed to consider the daily production fluctuations, as well as the differentiated operation costs of production units.

Each day is usually divided into 24 intervals [OMIE, 2015], referring to one hour periods. Market players submit their selling or buying bids for each hourly period. In the case of symmetric pools, both seller and buyer bids define the amount of power and the acceptable price (minimum price, for seller bids, and maximum price for buyer bids). On the other hand, in the case of asymmetric pools, buyer bids only contain the desired amount of power, while sellers' bids still specify also the price.

After the negotiation, the market operator sets the economic dispatch for each period. The market operator is responsible for the daily market correct functioning, starting and controlling the entire process. This entity is also liable for the market price definition, *i.e.* the price for the transactions in each period.

Symmetric pool

In symmetric pool market's price definition is based on a double auction mechanism, being therefore characterized by a competition between buyer and seller agents.

The market operator orders the supply and demand offers: the supply bids are sorted from the lowest price to the highest; and the demand bids are ordered from the highest price to the lowest. The supply and demand step curves are established and the market price is defined according to their intersection. The market price is uniform for all the transactions within the same period. The supply bids offering prices lower than the established market price will be accepted, as well as the demand bids offering prices higher than the market price. Depending on the demand, the last seller to trade, *i.e.* the one who establishes the market price, may not be able to negotiate all of its available supply, trading only partially.

This process is repeated for each trading period of the day. Figure 2.1 illustrates the economic dispatch procedure of the symmetric pool.

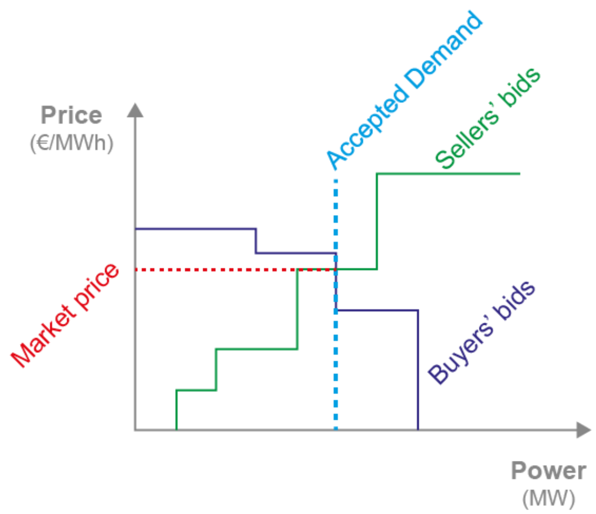


Figure 2.1 - Symmetric pool, adapted from [Praça *et al*., 2003]

The efficiency of this market pool depends on the number of participating players, as well as on their bids provision. Players submitting their bids in this type of market reveal the existence of behaviours with price sensitive consumptions.

Asymmetric pool

In asymmetric pool buyers only indicate an estimate of their consumption needs. In this model the demand is considered inelastic, since it is assumed that buyers participating in it are willing to pay any price resulting from the market operation.

In this market type, seller agents submit their bids and the market operator orders them from the lowest price to the highest. Afterwards, the market operator accepts only the supply necessary to fulfil the demand. The price to be paid to all the accepted suppliers is determined by the last accepted bid, *i.e.* the market price.

Figure 2.2 demonstrates the dispatch procedure of the asymmetric pool, for each negotiation period.

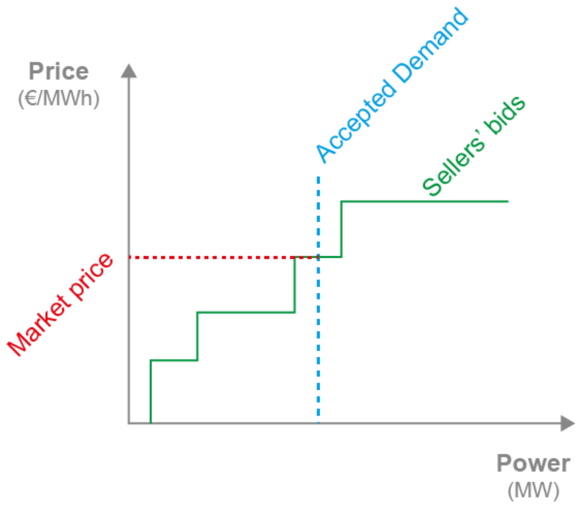


Figure 2.2 - Asymmetric pool, adapted from [Praça *et al.*, 2003]

The market prices in this type of pool are highly influenced by the prices offered in the selling bids and also by the amount of demand.

2.2.1.2 Intraday market

The intraday (or balancing) market [Olsson and Soder, 2008], [Veen and Vries, 2008] aims at correcting possible deviations from the forecasted production or consumption, taking care of the needed adjustments on the daily program and the last final hourly program. It is a market of voluntary participation. However, its participations is limited to players who have participated in the daily market's corresponding session; or which executed a bilateral contract; or whose production units were unable to attend the daily market due to unavailability. In other words, the intraday market is a complementary platform of the day-ahead market.

An important feature of this type of market is that buyers are able to sell in the intraday market while sellers are able to buy, depending on their strategies and consumption or production needed adjustments. Thus, players are able to take advantage of this market by defining negotiation strategies which consider selling more than they are capable of producing, when the prices are high, and after buying the extra amount on the intraday market with lower prices; or vice versa, buying a higher amount of power when the prices are low, in order to sell it in a later session at higher prices.

2.2.1.3 Complex bids

Complex conditions [OMIE, 2015], [Santos *et al.*, 2011] provide the means for players to present restrictions that, if are not met, allows them to leave the market, since they are not interested in participating unless those conditions are respected.

These type of bids can be used both in the daily or intraday market, and depend on the market itself, *i.e.* each market (Iberian, Italian, Central Western European, Northern European, etc.) implements its own complex offers or conditions. For instance, while MIBEL [OMIE, 2015], [Santos *et al.*, 2011], [Santos *et al.*, 2012] defines *complex conditions* and its rules for each of the pool markets (day-ahead and intraday), EPEX and Nord Pool delineate *block* and *flexible orders* [EPEX, 2015], [Fernandes *et al.*, 2014], [Nord Pool, 2015], [Santos *et al.*, 2015b].

Regardless of the relevant market, the market operator must ensure the economical dispatch taking into account the restrictions specified by each player. Such may lead to renegotiation of a period or even of all day, depending on the possible removal of players that have submitted competitive bids but whose complex conditions have not been met. The complex conditions of each of the markets mentioned above is succinctly described in subsection 2.2.2.

2.2.1.4 Bilateral contracts

The floor for bilateral contracts enables players to directly negotiate with each other, out of the scope of the spot market. It gives players the chance to reach advantageous agreements when, for example, trading with players that are within the same location. Bilateral contracts are also a good opportunity for players to establish contracts with varying timelines, resulting in increased security for companies that require constant demands over time; thus reducing the risk associated with the volatility of market prices.

When a player wishes to participate in the bilateral market, he contacts potential players offering his power and price proposal. The target players analyse the proposal and, if interested, they can accept it or try to renegotiate it. Before reaching an agreement, the supplier must be sure that it is feasible to deliver energy in the buyer's location, and for that the system operator's feedback is needed.

2.2.2 Relevant European markets

EM in Europe are tending to become more and more alike, in order to ease the accommodation to the unification of these markets. In the scope of this work, three of the most relevant

European EM have been considered, namely through their integration in MASCEM. These markets' most important characteristics are presented in this subsection.

2.2.2.1 MIBEL - Iberian market

The MIBEL day-ahead market consists of 24 hourly periods per day. The Iberian system is treated as a single system defining the same market price for both Portugal and Spain. However, when there are congestions on the interconnection between both areas, a split mechanism is used, enabling the best possible use of the available interconnections capacity, which may result in a distinct market price per area [OMIE, 2012].

A buying or selling bid can be carried out based on 25 offers per period. Regular bids feature for each offer a price and amount of power. If it is a selling bid, the price shall increase in each offer, while if it is a buying bid the price must decrease. As already detailed in section 2.2.1.3, the selling bids may include complex conditions, constraining the players' participation in the market if those conditions are not met.

In the Iberian market, the complex conditions are different from other important EM and have different rules depending on the type of market to perform [OMIE, 2015], [Santos *et al.*, 2011], [Santos *et al.*, 2012]. In the case of the daily market, bids may also include one or some of the following technical or economical restrictions: *Indivisibility*, *Load gradient*, *Minimum income* and *Scheduled stop*.

The *Indivisibility* condition enables setting a minimum operating value in the first offer of each period. Below this value, the participation of the production unit in the market is not possible. If the price is other than zero this value may be divided by applying distribution rules. This condition applies to generating units that cannot work under a minimum technical limit.

The *Load gradient* condition allows establishing the maximum difference between the energy sold by a production unit in consecutive periods. This allows avoiding abrupt changes, resulting from technical impossibility of the production unit in achieving such changes.

The *Minimum income* condition ensures that the production unit does not participate in the daily matching result if it cannot obtain a minimum amount, in Euros, in the total of all periods, plus a variable fee per transacted MWh. This restriction depends on the sales strategy of each player.

The *Scheduled Stop* condition is used in situations when the production unit has been withdrawn for not meeting the condition of required *Minimum Income*. This condition ensures that the production is not stopped abruptly, rather undertaking a scheduled stop in a maximum time of 3 hours, avoiding production to immediately decrease to zero, from the last period of one day to the first period of the next. This is done by accepting the first offer of the first three periods as a simple offer, with the sole condition that the offered power is decreasing in each period, to smooth the production decrease until it gets down to zero.

In day-ahead market, only seller players may present complex conditions. And whenever a complex condition is not met for a particular player, the period or day in matter is renegotiated, since the supply of this player may be changed or removed.

Regarding the intraday market, although being very similar to the daily market, it contains 6 market sessions, where players can renegotiate previously negotiated periods in the spot market, in order to fit their needs. The first session of the market sets the price adjustments for the last 3 hours of the trading day and for the 24 hours of the following day; in the second session the price for the 24 hours of the following day may be adjusted; the third session sets the adjustments for 20 hours: between the 5th and the 24th hour of the following day; the fourth session adjusts the price for the 17 hours between the 8th and the 24th hour of the following day; the fifth session adjusts the price for the 13 hours between the 12th and 24th hour of the following trading day; and finally, the sixth session sets the price adjustments for the 9 hours between the 16th and 24th hour of the following trading day [OMIE, 2015]. In this market type buyers are allowed to sell and sellers are allowed to buy.

In intraday markets different complex conditions are available for both buyers and sellers. The complex offers to sell are those that fulfil the requirements for simple offers, incorporating at least one of the following conditions: *Load gradient*, *Minimum income*, *Complete acceptance in the matching process of the first block of the sale bid*, *Complete acceptance in each hour in the matching period of the first block of the sale bid*, *Minimum number of consecutive hours of complete acceptance of the first block of the sale bid*, and *Maximum matched power*.

The *load gradient* and *minimum income* conditions are the same as those described before for the day-ahead market.

The *Complete acceptance in the matching process of the first block of the sale bid* condition enables sellers to trace a minimum profile of sales for the trading period, *i.e.*, to establish a minimum value for each hour. The player will enter the market only if this minimum is traded in all periods. This type of offer is associated with a high risk, whereas if the first tranche is not traded in one hour, the agent will be removed from the market in all periods of negotiation.

The *Complete acceptance in each hour in the matching period of the first block of the sale bid* condition is equivalent to the *Indivisibility* condition of the daily market. This condition sets a minimum value for the first tranche of each hour of operation, below which the participation of the production unit in the market is not possible; therefore the offer made for the remaining hours is not withdrawn. This condition is related to technical limits of generating units and it is constant for all time periods. The main difference from the *Complete acceptance in the matching process of the first block of the sale bid* condition is that, in this case, if the first tranche of one period is not traded, it does not mean the player must leave the market, and the power can be traded in the remaining periods.

The *Minimum number of consecutive hours of complete acceptance of the first block of the sale bid* condition is applied when a production unit must function consecutively in a minimum number of hours.

The *Maximum matched power* condition enables the production units to limit the traded amount to a global maximum energy value throughout the session. This is useful for units that present restrictions in the availability of the primary resource (for example, a reserve of water in a hydroelectric central).

Regarding the complex offers to buy, they fulfil the requirements of simple offers, and may incorporate all, some or any of the following conditions: *Load gradient*, *Maximum payment*, *Complete acceptance in the matching process of the first block of the purchase bid*, *Complete acceptance in each hour in the matching period of the first block of the purchase bid*, *Minimum number of consecutive hours of complete acceptance of the first block of the purchase bid*, and *Maximum matched power*.

These conditions are similar to those exposed before for the sale bids, but from the buyers' perspective, except in the case of *Maximum payments* condition, which is not matched if the total cost is above a fixed amount, in Euros, plus a variable remuneration per MWh traded. This constraint depends on the negotiation strategy of each player.

2.2.2.2 EPEX Spot

The EPEX Spot market is similar to MIBEL. It is a symmetric market, where the minimum and maximum bid prices are -500 and 3000 Euros respectively. It allows two types of offers [EPEX, 2015]:

- Individual hours: simple orders, similar to the bids of MIBEL, without complex conditions. These may contain up to 256 combinations of price/amount of energy for each hour of the auction;
- Block orders: with the purpose of connecting various periods. The offer is accepted in all periods or is rejected altogether. These present a lower priority when compared to simple orders.

In the case of EPEX [EPEX, 2015], [Santos *et al*., 2015b] no complex conditions are defined, for assuring some restrictions market players may use *Block orders*. *Block orders* are intended to connect several periods on an all-or-none basis, meaning that either the offer is accepted in all periods or it is rejected altogether. These offers have a lower priority when compared with the regular hourly offers. A block order is executed or not by comparing its price with the volume-weighted average of the hourly market prices related to the hours contained in the block. There are packages of block offers defined by standard, such as: ***Baseload** Block,* covering hours 1 to 24; ***Peakload** Block,* covering hours 9 to 20; ***Morning** Block,* covering hours 7 to 10; ***Evening** Block,* covering hours 19 to 24; ***Off-Peak** Block,* covering hours 1 to 8 and 21 to 24; among others.

There is also the possibility of defining custom blocks from linking a minimum of 2 consecutive periods. A maximum of 40 block orders per player per day can be submitted and the maximum volume for a block order is 400 MW.

2.2.2.3 Nord Pool Elspot

The Elspot market from Nord Pool is also an auction based market, where both buyers and sellers present offers, *i.e.* it is also a symmetrical market. The offers must be contained in the price range set by Nord Pool Spot. Elspot enables three possible types of offers [Nord Pool, 2015]:

- Hourly Orders: similar to the simple, per period offers in MIBEL and EPEX spot, but considering 64 combinations of price/amount of power;
- Block Orders: similar to EPEX Spot block offers;
- Flexible Hourly Orders: give the opportunity to present sale offers only, without indicating a specific period for the same, *i.e.* these volumes can be transacted in any period of the day, depending on the offer price, and on the necessities of the market for each period.

Nord Pool [Fernandes *et al.*, 2014], [Nord Pool, 2015], supports the submission of *Flexible hourly orders* in addition to *Block orders*. The supported *Block orders* are similar and have the same behaviour as the ones presented in EPEX. Concerning the flexible orders, a *Flexible hourly order* is a single sale offer (purchases are not allowed) where sellers specify only the price and amount of energy to trade. The period is not indicated as this type of order is accepted in any period of the day, depending on the optimization of the overall socioeconomic welfare of the market.

The negotiation process is similar to MIBEL's and EPEX's markets. For flexible offers, trading occurs in the same way as with the hourly orders, and these deals will apply in the period when its use maximizes the overall market's social welfare. Regarding the block offers, they will be accepted if the market price of all periods in which the block applies is equal to, or higher than, the price of the block bid, for selling offers; or if the market price of the block periods is equal to, or less than, the price of the block, for purchasing bids. This condition is called *fill-or-kill*.

Table 2.1 demonstrates a general comparison of the main characteristics of the presented EM mechanisms. As it is possible to observe in Table 2.1, many rules are similar between the three markets. Some have been updated recently to assure the market's rules harmonization.

Recently, the integration of European regional EM in a Pan-European market has become a reality [EMCC, 2015]. One of the key elements of the recent market coupling is the newly developed unique single price coupling algorithm – EUPHEMIA [EUPHEMIA, 2015] – that has been developed by the Price Coupling of Regions (PCR) Project [PCR, 2015]. The EUPHEMIA algorithm takes into consideration the main types of orders of each participating European regional market, so that players in each region may continue to present their bids in the same way they did so far.

Table 2.1 - Day-ahead EM comparision

	Nord Pool Elspot	**EPEX Spot**	**MIBEL**
Bidding deadline	12h CET	12h CET - Austria/Germany and France 11h CET - Swiss	12h CET
Bidding Periods	24 periods (1 hour periods)		
Maximum Price	3000 EUR/MWh	3000 EUR/MWh	180.3 EUR/MWh
Minimum Price	-500 EUR/MWh	-500 EUR/MWh	0 EUR/MWh
Minimum Bidding Volume	100 kW	100 kW	1 MW
Number of Bids for the same period	64	256	25
Bidding types	Single hourly orders; Block orders; Flexible hourly orders	Hourly orders; Block orders	Simple Bids Complex Bids (Indivisibility; Minimum income; Scheduled stop; Load gradient)
Areas	16	3	2

The increasing complexity brought by such a diversity of market types has resulted in significant changes concerning the relationship between the electricity sector entities. It has also resulted on the emergence of new entities, mostly dedicated to the electricity sector and electrical energy trading management. In what regards the commercial transactions, the analysis of different market mechanisms and the relationship between market entities becomes crucial. All market participants develop interactions among them, needing information systems for that purpose. As the observed context is characterized as being of significant adaptation and change, the need for decision support tools directed to this markets' analysis is also accentuated. Multi-agent based software is particularly well fitted to analyse systems with such characteristics [Wooldridge, 2002].

2.3 Agents and Multi-agent systems

The term Distributed Artificial Intelligence (DAI) emerged in the early 80's, resulting from the merging of Artificial Intelligence (AI) and Distributed Computation. This field was created with the purpose of solving problems for which a single entity equipped with AI could not provide the appropriate response [Davis, 1980].

According to Panait and Luke [Panait and Luke, 2005], the DAI is divided into two key areas: the Distributed Problem Solving and MAS. The former relates to the decomposition and distribution of a problem solving process with multiple knots, regarding a collective solution for the problem. The following is focused on the widespread behaviour of software agents and their interactions, from which results some degree of autonomy and complexity. These systems regard the coordination of intelligent behaviours displayed by a community of agents, so that they are able to share knowledge, resources, abilities, plans and goals in order to perform particular actions and/or solve complex problems. Furthermore, individual agents should be capable of reasoning about the involved coordination processes.

The concepts of Agent and MAS are described below in order to provide a clarification of what an agent is, which are their typical characteristics, and how agents can be organized in the presence of other agents.

2.3.1 The (Software) Agent

There is no common definition of agent in AI literature, probably because each definition came directly from the application area [Huang *et al.*, 2009], [Schleiffer, 2005]. Minsky [Minsky, 1986] argues that each agent is only able to perform simple tasks that do not demand reasoning. However, when these agents are instated in societies, it will lead to real intelligence. On the other hand, Brustolini [Brustolini, 1991] claims that agents are defined as systems that are capable of autonomously performing important actions in the real world. To effectively do so, agents must develop strategic decision making capabilities to coordinate their actions [Coelho, 1994]. Agents' autonomous actions are based on information collected from the environment (sensors, feedback, among others) [Panait and Luke, 2005].

Nevertheless, some of the agent characteristics are consensual in the numerous definitions. A common accepted definition is that an agent is a computer system in a particular environment, with which it interacts through sensors and actuators, trying to accomplish its design goals, thus acting reactively and proactively [Wooldridge and Jennings, 1995], [Wooldridge, 2002]. Agents can be classified according to a set of features that allow them to achieve their goals [Weiss, 2010]:

- Sensorial capability – an agent has sensors to gather information about its environment;
- Reactivity – an agent feels and acts, reacting to on-going environment changes;
- Autonomy – an agent decides and controls its own actions;
- Pro-activity – an agent is goal driven, and goes beyond reacting to the environment;
- Persistency – an agent exists during long periods of time;
- Social skills – an agent communicates and cooperates with other agents or even people, *i.e.* competing or negotiating;
- Learning – an agent is able to change its behaviour based on prior experience;

- Mobility – an agent is able to move from one computer to another;
- Flexibility – the agent's tasks don't need to be pre-determined;
- Agility – an agent is able to swiftly take advantage of new unforeseen opportunities;
- Character – an agent presents a credible personality and emotional behaviour;
- Intelligence – an agent is able to reason autonomously, to plan its actions, to correct its mistakes, to react to unexpected situations, to adapt and to learn.

Other characteristics that agents should have are described by some authors [Cui-Mei, 2009], [Huang *et al.*, 2010], such as:

- Personalization – an agent is able to represent an entity's information and behaviour;
- Rationality – an agent must maximize its achievement and try to fulfil its goals successfully;
- Veracity – or honesty, an agent cannot intentionally pass false information;
- Sanity – an agent only takes actions helpful to achieve its goals, and doesn't take them blindly.

2.3.2 Multi-Agent Systems

Single-agent systems are very useful as stand-alone entities performing tasks delegated by a user, freeing him from hard work [Cui-Mei, 2009]. Most often, agents coexist in environments containing other agents and interacting with each other, thus composing a MAS.

MAS are considered dynamic since the environment may change with an agent's interaction. Reliability, robustness, modularity, scalability, adaptability, concurrency, parallelism, and dynamism are some of the advantages MAS present over single-agent systems [Elamy, 2005]. The aim is to split complex problems into simpler subtasks and distribute them between individual software entities, allowing to distribute the systems' intelligence across several components instead of being concentrated in a single point [Trichakis, 2009]. The growth of the Internet and Web Computing significantly increased the popularity of MAS since they represent an environment in which agents may exist and interact with each other, taking advantage on agents' distributed nature to deal with complex dynamic problems. MAS work differently from distributed control systems since decision making usually occurs locally and autonomously. Only when necessary, a MAS requires inter-agent communication; which occurs more often among agents with common interests [Trichakis, 2009].

2.3.2.1 Standards and Interoperability

When designing MAS, the use of standards that promote interoperability between systems is becoming increasingly important, if not even compulsory [McArthur *et al*., 2006], [McArthur *et al*., 2007]. The Foundation for Intelligent Physical Agents (FIPA) [FIPA, 2014] *"is an IEEE Computer Society standards organization that promotes agent-based technology and the* *interoperability of its standards with other technologies"*, officially at the Institute of Electrical and Electronics Engineers (IEEE) since June 2005.

FIPA develops and promotes standards that enable interoperability between heterogeneous agent-based systems [FIPA, 2002a], [FIPA, 2014]. Its standards include not only the basis of MAS architecture, establishing the types of agents a MAS should have to be FIPA compliant [FIPA, 2003a]; but also methods to support inter-agent communication, such as standards for agent communication language [FIPA, 2002a], communicative acts [FIPA, 2002b], content languages [FIPA, 2003b], and message transport protocols [FIPA, 2003a]. However, FIPA does not specify how an agent attains its reasoning.

FIPA provides an open and scalable architecture where agents can be easily added or removed allowing new functionalities to be included in the system just by replacing the existing agents with improved ones. This ability is especially important when considering the upgrade of the MAS with the minimum complexity [Trichakis, 2009].

Following these standards, agents from heterogeneous platforms should be able to interoperate. Which does not mean that the agents are able to exchange any useful information, unless they use the same ontology. Even if the agents use the same communication language and content language, if they do not share a common vocabulary, they will not be able to interpret the incoming messages, nor to communicate effectively.

Agents should use the same communication language and common ontologies in order to be able to interact. Agents should also be able to communicate when using different but translatable ontologies. MAS should be minded to support this kind of communication. Additionally, aiming at efficiency, the communication platform should incorporate several services such as Communication Services (the message exchange mechanism; synchronism; pooling; forwarding), Conversation Services (timeout mechanisms; information management and synchronization), Directory Services (White pages; Yellow pages) and Security Services (names services; permissions services; message encryption services) [FIPA, 2004].

The development of MAS becomes an arduous and complex process due to the need for such standards and their requirements. Nevertheless, there are some multi-agent development platforms available that facilitate and improve the development and deployment of MAS, enabling the developer to focus his attention on the application area of the system itself.

2.3.3 Agent-based platforms, toolkits and frameworks

When developing agent-based systems the choice of a programming language becomes essential. According to Ivanovic and Budimac [Ivanovic and Budimac, 2012] agent-based platforms are software packages that provide the main features for deploying and running MAS, thus facilitating their development and deployment. On the other hand, agent toolkits are more complex infrastructures, sometimes known as agent development environments, because they are expected to support all engineering stages of an agent-based application, from requirements to deployment, maintenance and evolution. Finally, an agent framework is a language environment, software library, or both, supplying the core software needed for developing the MAS backbone. Some examples of agent-based development kits are ZEUS [Nwana *et al.*, 1999], FIPA-OS [Poslad *et al*., 2000], OAA [OAA, 2015] and JADE [JADE, 2015].

The communication and coordination (cooperation or competition) with other agents is fundamental for autonomous agents in a MAS. Communication is a prerequisite for coordination between agents, achieved through the exchange of messages using an agent communication language. There are several available communication languages and formats, *e.g.* FIPA-ACL (Agent Communication Language); KIF (Knowledge Interchange Format); KQML (Knowledge Query and Manipulation Language); and ICL (InterAgent Communication Language). These provide important parameters such as technical declarations (*e.g.* sender and receiver), speech acts (*e.g.* propose, accept, query and inform) and content language (*e.g.* predicate logic).

ZEUS is a FIPA-compliant agent toolkit to develop and organize MAS. It consists of *"a set of components, written in the Java programming language, that can be categorised into three functional groups (...): an agent component library, an agent building tool and a suite of utility agents comprising nameserver, facilitator and visualiser agents"* [Nwana *et al.*, 1999]. It enables a rapid development of collaborative agents through the supply of a library and an environment to support the agent implementation process. ZEUS agents communicate using the 1997 FIPA-ACL specification [ZEUS, 2000] which applies SL (Semantic Language) as content language [FIPA, 1997]. These are nowadays obsolete and have been replaced by the *FIPA 2000 and Beyond* specifications.

FIPA-OS (Open Source) [Poslad *et al*., 2000] is an open agent platform that uses an agent communication language which conforms to FIPA standards. A key element is its support for openness. FIPA-OS is distributed and managed under an open-source license. FIPA-OS was implemented in various fields, including virtual private network provisioning, distributed meeting scheduling and a virtual home environment. It has been shown to interact with other heterogeneous FIPA compliant platforms and has been used in various institutions worldwide. FIPA-OS also uses FIPA ACL as content language, but a more recent version [FIPA-OS, 2003]. And as content languages it accepts FIPA SL [FIPA SL, 2001], FIPA CCL [FIPA CCL, 2001], and FIPA RDF [FIPA RDF, 2001]. FIPA CCL and FIPA RDF are still *Experimental* while FIPA SL is already a FIPA *Standard* since 2002.

Open **A**gent **A**rchitecture (OAA) [OAA, 2015] is presented as *"A framework for integrating a community of heterogeneous software agents in a distributed environment."* It was developed aiming for the integration of heterogeneous software agents in distributed environments. OAA provides the dynamic and extensive nature of black board based systems, the efficiency of moving objects and consequently the dynamism of the agents' interactions. The inter-agent communications in OAA are carried out through the InterAgent Communication Language (ICL), a logic-based declarative language capable of expressing high-level, complex tasks and natural language expressions. It includes a conversational protocol similar to KQML's communication layer which is defined by event types and respective associated parameters list. In turn, the content layer is analogous to the one available in KIF and consists of the specific goals, triggers, and data elements that may be embedded within various events. MAS developed in OAA rely on the *Facilitator agent* which can be considered a weakness, as it is a bottleneck. This issue can, according to [OAA, 2015], be mitigated by multiplying the number of facilitators.

JADE (**J**ava **A**gent **DE**velopment Framework) *"is an open source platform for peer-to-peer agent based applications"* [JADE, 2015] and was developed with the aim of achieving a FIPA-compliant framework that facilitates the extensibility as well as the compatibility of MAS developed following the FIPA specifications. It provides: agent abstraction; a simple but powerful task execution and composition model; peer to peer asynchronous agent communication; yellow pages service supporting publish, subscribe and discovery mechanisms; among many other advanced features that ease and reduce the effort needed to develop an agent-based system. JADE authors argue that a peer-to-peer architecture reduces failure situations unlike architectures that depend on a single entity. Agents in JADE communicate through the exchange of messages using FIPA ACL language. Regarding the content language, FIPA-SL is the default language although the use of other strings such as object serialization, XML and RDF is also allowed [Bellifemine *et al.*, 2004], [JADE, 2015].

2.4 Semantics for multi-agent interoperability

Software agents are commonly defined as autonomous software entities that exhibit reactive and proactive behaviours and are placed in some environment [Wooldridge and Jennings, 1995]. Agents are usually part of MAS, and they should be able to interact with other agents to coordinate their actions and share knowledge. In other words, agents should interact with each other regardless of how they represent and interpret their own knowledge.

Agent-to-agent communication of heterogeneous agents faces interoperability problems concerning the integration of ontologies of different domains and also different ontologies of the same domain [Schiemann and Schreiber, 2006].

Semantic interoperability is a major challenge due to semantic heterogeneity. The semantic heterogeneity arises when distinct ontology designers develop different ways of conceptualizing the knowledge (which can be motivated by different needs), giving rise to different conceptualizations, which are sometimes incompatible. Several types of conflicts may cause semantic inconsistencies, such as: name, structure, attributes, granularity of values, among others [Wiederhold, 1997]. Therefore, semantic interoperability should go beyond and understand the deeper meaning of terms.

2.4.1 Ontology

One of the most agreed definition of ontology in AI is: "*Ontology is an explicit specification of a conceptualization*" [Gruber, 1993]. A few years later, Brost [Brost, 1997] (re)defined ontology as "*a formal and shared specification of a conceptualization*", defending that the conceptualization should express a *shared* view between several parties (*i.e.* a consensus instead of an individual view), and also, it should be expressed in a *formal* (machine readable) format.

In 1998, Studer *et al.* [Studer *et al.*, 1998] merged these two definitions, stating: "*An ontology is a formal, explicit specification of a shared conceptualization*", where:

- *Conceptualization* is the domain's abstract and rational model, including the identification and description of concepts, properties and relations between them;
- *Specification* is the detailed, accurate, consistent, solid and meaningful description of a domain;
- *Explicit* is the representation of the conceptualization in a way software agents can understand and reason upon it;
- *Formal* implies that both human and machines are able to read, understand and process the ontology;
- *Shared* means that the ontology is accepted consensually by a group and not only by an individual.

The term ontology has gained significant popularity in the last twenty years due to its promise of achieving interoperability between several representations of reality and between those representations and reality [Hepp, 2007]. On the other hand, ontologies enable knowledge sharing and its reuse across distinct communities of both human and software agents [Essalmi and Ayed, 2007].

An ontology is the vocabulary and the formal specification of the vocabulary of a specific domain [Hepp, 2007]. It allows representing knowledge in an abstract and organized way, providing a common understanding between heterogeneous entities. Furthermore, by means of inference engines it provides computational inference on both conceptual model and stored data, enabling the automatic generation of new information.

Although the promises of ontologies are broad, in fact they are not the solution for all problems. Ontologies have a useful life cycle and require maintenance, and there are situations where the cost of development and maintenance of an ontology is too high [Hepp, 2007]. Gruninger and Lee have summarized the use of ontologies as follows [Gruninger and Lee, 2002]: "*(…)*

- ***for communication***
    - *between implemented computational systems*
    - *between humans*
    - *between humans and implemented computational systems*

- ***for computational inference***
    - *for internally representing plans and manipulating plans and planning information*
    - *for analyzing the internal structures, algorithms, inputs and outputs of implemented systems in theoretical and conceptual terms*
- ***for reuse (and organization) of knowledge***
    - *for structuring or organizing libraries or repositories of plans and planning and domain information.*"

It is noteworthy that ontologies, in addition to providing more than a basis for computational inference, are also useful for improving interaction between human actors and between human actors and computational systems [Hepp, 2007].

2.4.2 Upper Ontology overview

An upper, top-level or more accurately foundational ontology, is a high level ontology that addresses very general domains (*e.g.* time, space, inherence, instantiation, identity, measure, quantity, functional dependence, process, event, attribute, boundary, among others) [Masolo *et al*., 2003], [Smith, 2004], supporting a broad semantic interoperability between lower level ontologies derived from it. It should serve as a common neutral backbone, which would be complemented by ontologies of more specific domains, such as medicine, engineering and geography.

Upper ontologies are intended to facilitate interoperability and mutual understanding between people and machines, including the comprehension of the reasons for non-interoperability. These motives are sometimes more important than developing an integrated system based on a generic shared "semantics", but conceptually imperfect and unpredictable [Masolo *et al*., 2003]. The entities (*i.e.* concepts and relationships) covered by the upper ontology must be abstract enough since these ontologies are supposed to cover all relevant knowledge aspects of each entity's domain.

2.4.3 FIPA Ontology Service Specification

FIPA's agents' communication model is based on the assumption that two agents wishing to exchange messages share a common ontology for the subject domain, ensuring that agents assign the same meaning to the message's symbols [FIPA, 2001].

FIPA proposes the use of an Ontology Agent (OA) for MAS environments. FIPA defined that the OA should be able to participate in communications by assuming the following tasks (although the OA's answer may be that it is not able to execute any or some of these tasks) [FIPA, 2001]:

- help a FIPA agent in the selection of a shared (sub)ontology for communication;

- create and update an ontology, or some terms of the ontology;
- translate expressions between distinct ontologies (*i.e.* different names with the same meaning);
- respond to queries about relationships between terms or ontologies;
- discover public ontologies in order to access them.

The OA is expected to provide access to one or more ontology servers which, in turn, provide ontology services to the agent community.

Designers may decide to develop explicit and declaratively represented ontologies, stored somewhere, or alternatively, implicitly encoded ontologies which are not published in an ontology service. Also, for a given domain, it is possible to use ontologies implicitly encoded within the agent's implementation, and full agent communication and understanding can still be achieved. However, in these cases, the services provided by the OA cannot be applied [FIPA, 2001].

It is not FIPA's intention that every MAS includes an OA, but in order to promote interoperability, if the OA exists in the agent's community, it must be compliant with FIPA's specification as well as the services described in [FIPA, 2001]. FIPA Ontology Service Specification [FIPA, 2001] is platform independent and only determines the way agents access an ontology service. In order to allow the communication of knowledge between agents, an explicit representation formalism has been specified, *i.e.* the *FIPA-Meta-Ontology* [FIPA, 2001]. This (FIPA Ontology Service Specification) is still an experimental specification which means that it is not yet a FIPA standard, and its use is not mandatory for a MAS to be FIPA compliant.

Ontologies, thereby, provide important perspectives of interoperability between different systems, by enabling a correct interpretation of agents' messages, thus facilitating the interaction between agents of distinct natures and characteristics. This is a crucial requirement for the effective study of highly complex and dynamic systems, containing a large number of different types of agents with a high volume of interactions between them, such as the power system environment, and EM in specific.

2.5 Multi-agent simulation of electricity markets

The restructuring of EM during the last decades, has increased the need for simulation tools for the study and better understanding of these liberalized markets. EM simulators must be flexible in order to handle this complex and evolving reality, providing players with proper tools to adapt themselves to this dynamic reality and learn from experience.

Agent-based simulators should allow easy extensibility of the models so that future evolution of these markets may be accomplished. Several studies sustain that MAS with the adequate simulation capabilities are suitable for the simulation of wholesale EM, considering the complex interactions of the involved players, *e.g.* [Koritarov, 2004], [Li and Tesfatsion, 2009], [Migliavacca, 2007]. It is noteworthy that a MAS is not necessarily a simulation platform, but simulations may take advantage of this distributed systems characteristics, namely in the study of EM, where each player has its own goals and beliefs and compete or collaborate with other players, and interacts with the respective operators. This is of crucial importance for the entities involved in EM, concerning namely scenarios comparison, markets evolution studies and sensitive analysis.

The Simulator for Electric Power Industry Agents (SEPIA) [Harp *et al.*, 2000] is a simulator oriented for Microsoft Windows platforms and is based on a Plug and Play architecture. It allows users to readily create simulation scenarios wrapping various machines in a network using several processing units, or in a single machine. The number of participating agents is specified by the user, as well as their behaviours, interactions, and changes during the simulation. SEPIA provides mechanisms to follow and guide the simulation developments.

The Electricity Market Complex Adaptive System (EMCAS) [Koritarov, 2004] applies an agent based approach where the agents' strategies are based on learning and adaptation. The agents model the restructured EM heterogeneity, considering the generation, demand, transmission and distribution companies, independent system operators, consumers and regulators. EMCAS provides simulations in a time continuum ranging from hours to decades, including various market pools and bilateral contracts.

Power Web [Zimmermann and Thomas, 2004] is a Web-based market simulator, allowing the interaction of its participants from various parts of the world. It is a very flexible system that provides the definition of simulations considering a broad ensemble of scenarios and rules. To guarantee the system's reliability, it includes a centralized agent acting as an independent system operator, according to a defined group of entities, acting in several markets. It is also possible to participate in an open market where users compete against producers, controlled by other users or computational algorithms.

The Short-medium Run Electricity Market Simulator (SREMS) [Migliavacca, 2007] is a game theory based simulator capable of supporting scenario analysis in the short-medium term and, in some situations, to evaluate the market power. Some of its main features are: simulation of short-medium run EM, based on game theory, calculating price-makers optimal hourly bids; inelastic load, defined hour by hour and zone by zone; tree-like network with inter-zonal transit limits; monthly scheduling of reservoir hydro pumping storage plants; highly realistic representation of thermal plants; depending on producers share and risk attitude, possible quota appointed to physical bilateral contracts. SREMS is particularly suited for studying the Italian electricity market.

The Agent-based Modelling of Electricity Systems (AMES) [Li and Tesfatsion, 2009] is an open-source computational laboratory for the experimental study of wholesale power markets restructured in accordance with US Federal Energy Regulatory Commission (FERC)'s market design. To experimentally test the extent to which commonly used seller market power and market efficiency measures are informative for restructured wholesale power markets, AMES uses an agent-base test bed with strategically learning traders. It includes the independent system operator, load-serving entities and generation companies, distributed across the busses of the transmission grid. To update the action choice probabilities currently assigned to the supply offers in its action domain, each generation company agent uses stochastic reinforcement learning.

The Genoa Artificial Power Exchange (GAPEX) [Cincotti and Gallo, 2013] is an agent-based framework for modelling and simulating power exchanges. GAPEX is implemented in MATLAB and allows the creation of artificial power exchanges reproducing exact market clearing procedures of the most important European power-exchanges. This simulator is especially directed to the study of the Italian electricity market.

These are important contributions but, as they adopt a limited number of market models and of players' methodologies, they lack flexibility. It is hard to follow the evolution of these simulators but some of them are evolving in a very dynamic way, as is the case of AMES. It is important to go a step forward in EM simulators as this is crucial for facing the power systems' evolution. Due to high penetration of distributed energy resources and demand side participation, the increasing number and the diversity of active players are a huge challenge [Figueiredo *et al.*, 2005].

The Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) [Praça *et al.*, 2003], [Santos *et al.*, 2015a], [Vale *et al.*, 2011a] was developed with the goal of overcoming these challenges and overtake the limitations presented by the mentioned simulators. Section 2.6 overviews MASCEM in detail, pointing out its improvements and restructuring planned and implemented in the scope of this work.

2.6 Multi-Agent Simulator of Competitive Electricity Markets

MASCEM – Multi-Agent Simulator of Competitive Electricity Markets [Praça *et al.*, 2003], [Santos *et al.*, 2015a], [Vale *et al.*, 2011a] is a modelling and simulation tool which has been developed aiming at studying the operation of complex and competitive restructured EM. It models the main complex and dynamic market entities and their interactions. To support players' decisions in accordance with their characteristics and goals, medium/long-term gathering of data and experience is also considered. Figure 2.3 illustrates MASCEM's main features.

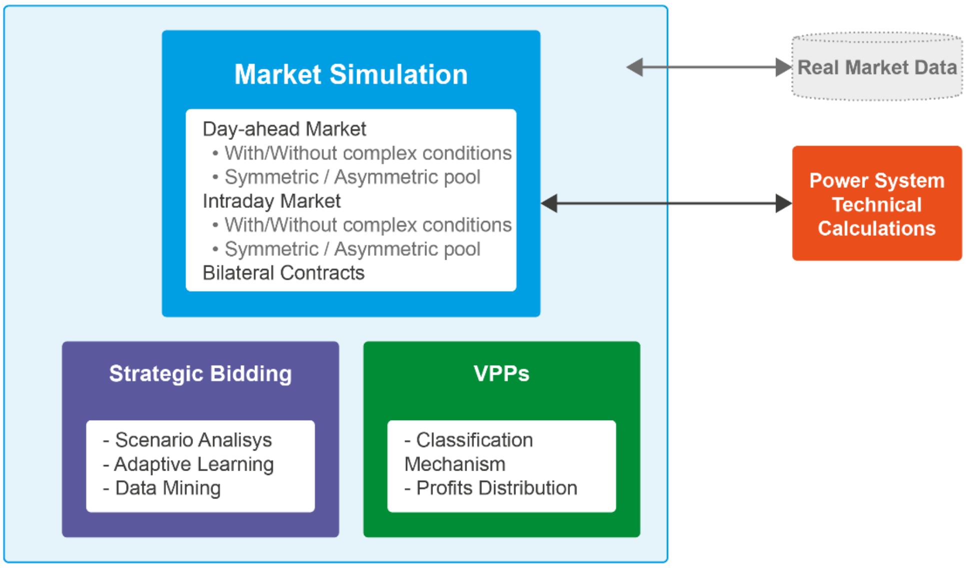


Figure 2.3 - MASCEM main features, adapted from [Pinto *et al.*, 2011]

MASCEM was implemented in Java [Java, 2015] on top of OAA [OAA, 2015], using OAA AgentLib library; with the OOA's Interagent Communication Language (ICL) as the interface and communication language shared by all agents, which allows integrating a variety of software modules and agents independently of which machine and operating system they are running on, or which programming language they are programmed in.

The communication and cooperation between the agents is made through facilitators. Facilitators are responsible for matching requests, from users and agents, with descriptions of the capabilities of other agents.

Since OAA is not a framework specifically dedicated to the development of simulation tools, some extensions have been made in order to introduce the time evolution mechanism of the simulation; and thereby make it suitable to deal with the energy markets paradigm.

MASCEM aims to simulate as many market models, players and operators as possible in order to emulate the real EM operation. Allowing it, therefore, to be used as a decision support tool for short/medium-term purposes and also for long-term decisions, as the ones taken by market regulators.

2.6.1 Multi-agent model

MASCEM's multi-agent model represents the main entities in the scope of wholesale EM and their relationships. It includes a market facilitator, the market and system operators, the market players - buyers and sellers -, virtual power players (VPP) [Praça *et al.*, 2007] and VPP facilitators. A general overview of MASCEM's multi-agent model, *i.e.* their entities and respective relationships, is shown in Figure 2.4.

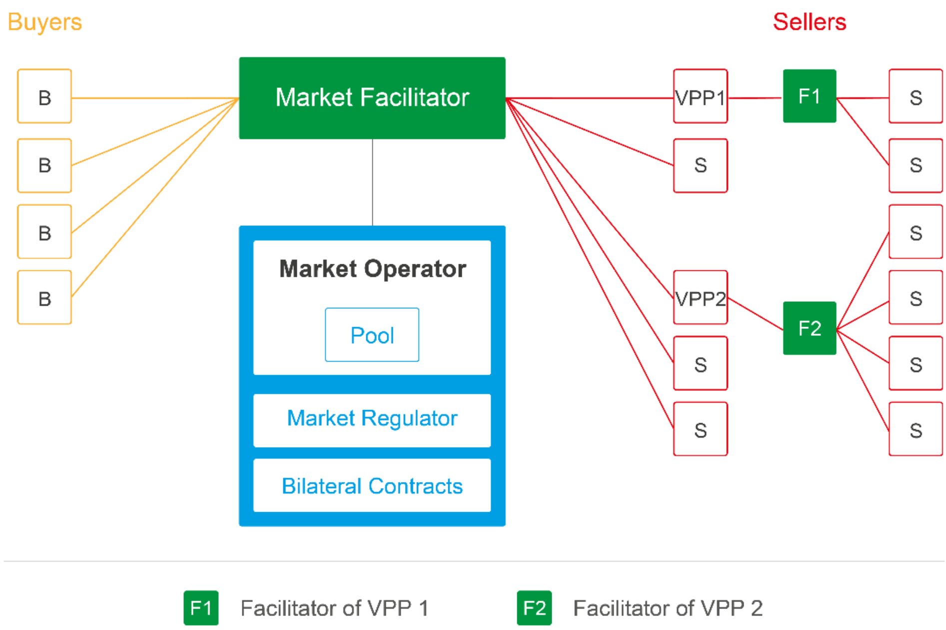


Figure 2.4 - MASCEM's multi-agent model, adapted from [Vale *et al.*, 2011b]

The market facilitator agent assures the proper operation of the market simulation by coordinating and regulating all existing communications. It knows all the agents present in the simulation, since they must register in advance at the facilitator, citing their roles and respective services.

The market operator agent is responsible for coordinating and regulating the pool markets operation. Thus, it is only present in pool or hybrid markets simulations. It informs buyer and seller agents when the pool is open, receives their proposals, validates and analyses them, and determines the clearing market price, accepted and refused bids for each trading period.

The system operator agent is responsible for the system's security and ensures that all constraints are satisfied within the system. It is always present during the simulations. After being informed by the market operator of the market's outcome, it examines the technical feasibility from the power system point of view and solves congestion problems that may arise. Actually, this agent makes use of a power system simulator which performs the power flow analyses [Ferreira *et al.*, 2007].

Buyer and seller agents – the market players – are the key elements of EM. Buyer agents represent the demand side entities, while generation units are represented by seller agents. On one hand, sellers compete with each other trying to increase their profits; on the other, they may also cooperate with buyer agents trying to reach agreements that are advantageous for both parties. The user defines the number of buyers and sellers, and their respective strategic features, for each simulation scenario.

Finally, the VPP agents represent alliances of small independent players. The meaningful increase of small independent producers and consumers participating in the market, brought the need to make such alliances to enable them competing with big producers. The VPP agent manages their aggregates information and is viewed in the market in the same way as buyer or seller agents. Each VPP is modelled as a distinct MAS, allowing agents to be installed on different machines while maintaining the high performance as possible. Individual VPP facilitators have been developed to manage the communications between the VPP and its members [Pinto *et al.*, 2009].

2.6.2 Electricity Markets simulation in MASCEM

MASCEM includes the main types of negotiations normally present in EM, such as: day-ahead and intraday pool (symmetric and asymmetric) markets; bilateral contracts; forward markets; and mixed markets. The negotiation sequence for a simulation day in MASCEM is presented in Figure 2.5.

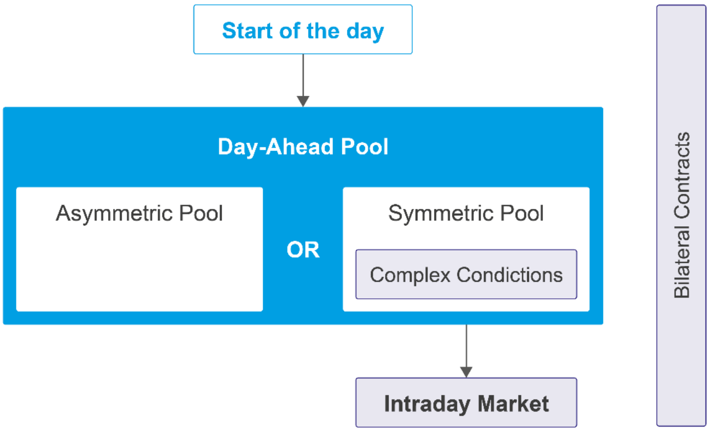


Figure 2.5 - MASCEM's negotiation timeline for a simulation day, adapted from [Santos *et al.*, 2012]

Simulation scenarios in MASCEM are automatically defined, using the Realistic Scenario Generator (RealScen) [Teixeira *et al.*, 2014]. RealScen uses real data that is available online, usually in market operators' websites. The gathered data concerns market proposals, including quantities and prices; accepted proposals and established market prices; proposals details; execution of physical bilateral contracts; statement outages, accumulated by unit type and technology; among others. By combining real extracted data with the data resulting from simulations, RealScen offers the possibility of generating scenarios for different types of EM. Taking advantage on MASCEM's ability to simulate a broad range of different market mechanisms, this framework enables users to consider scenarios that are the representation of real markets of a specific region; or even consider different configurations, to test the operation of the same players under changed, thoroughly defined scenarios [Teixeira *et al.*, 2014]. Realistic scenarios with a limited number of agents are obtained by using RealScen data mining techniques, namely clustering. Real players are grouped according to their similarities, resulting in a diversity of agent types that represent real market participants.

Aggregators are an important part of the future power system management and operation, introducing a higher level of complexity in the system. Some examples of such are: SG operators, which manage the players that are contained in a specific SG; Curtailment Service Providers (CSP), which aggregate consumers that participate in DR programs; and VPPs, which can aggregate any other resource, including other aggregators.

The VPPs' operation, coalitions' formation and management negotiations take place in distinct timings [Pinto *et al*., 2014a], [Vale *et al.*, 2011c]. These negotiations take into account the players' features, aims and goals, and enables them to make alternative deals to those they would make by trading exclusively on the market. This type of negotiations provides, both players and their aggregator, the capability of achieving more profitable coalition contracts.

2.6.3 Virtual Power Players

The use of renewable energy resources is increasing due to environmental and fossil fuels shortage concerns. From the environmental point of view, advantages are clear, but from the technical and economical perspectives, to take advantage of an intensive use of renewables (which are mainly distributed generation sources) there are issues that must be overcome. Aggregating strategies allow renewable generation companies to attain technical and commercial advantages, overcoming severe disadvantages of some technologies and making profit of the specific advantages of mixing several generation technologies. The VPP concept arises from the aggregation of distributed generation power plants; and its integration in the EM is a very challenging domain which motivates MASCEM's evolution.

VPPs are multi-technology and multi-site heterogeneous entities. The key factor for their success is the relationships between aggregated players and also among VPPs and other market players [Dang and Jennings, 2004], [Rahwan and Jennings, 2008], [Vale *et al*., 2008]. VPPs are seen as a coalition representing the aggregated players. The coalition is the union of autonomous entities that agree to cooperate and coordinate their actions to achieve a particular task, acting in unison, improving the system's performance, and the individual agents' as well. Three phases comprise the coalition formation process: coalition structure generation, optimization of the value of the coalition and payoff distribution [Oliveira *et al*., 2009], [Pinto *et al*., 2009], [Vale *et al*., 2008].

For VPP modelling, the three phases should be considered under a scenario where agents operate in a dynamic and time dependent environment, which implies meaningful changes on MASCEM's core model and communications infrastructure. To participate in the market, the VPP must forecast its aggregated players' generation and keep some power capacity to guarantee a reserve in case of need to compensate generation oscillations, which commonly occurs when using renewable resources technologies.

The modelling of VPPs in MASCEM enlarged the scope of negotiation procedures in this simulator, enabling the study of new types of negotiations outside the common EM regulatory models.

Despite VPPs allowed the study of coalitions, it has become necessary to allow further study of the actions that occur at a lower level. Since VPPs are not suitable for such study, a new simulator has been introduced, which adds the possibility of studying several topics on the smart grids (SG) level.

2.6.4 Multi-Agent Smart Grid simulation Platform

A smart grid (SG) can be defined as "*an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both, in order to efficiently deliver sustainable, economic and secure electricity supply*" [SGETP, 2013]. In turn, a microgrid (MG) is a low voltage distributed system integrating distributed energy sources, controllable loads and storage devices, being connected to the power system at a common coupling point, thus appearing to the grid as a single controllable subsystem [Hatziargyriou *et al*., 2014].

The Multi-Agent Smart Grid simulation Platform (MASGriP) [Oliveira *et al.*, 2012] is a MAS that models the internal operation of SG and MG. This system models all the typically involved players through software agents capable of representing and simulating their actions. MASGriP simulates, manages and controls the most relevant players acting in a SG and MG environment. Additionally, some small players are directly connected to physical installations, providing the means for an automatic management of the associated resources. This enables the development of a complex system capable of performing simulations with an agent society that contains both simulated players and real infrastructures, providing the means to test alternative approaches in a realistic simulation environment [Gomes *et al*., 2014a]. To complement simulations with the analysis of the impact of the methods in the energy flows and transmission lines, MASGriP uses real-time simulation [Fernandes *et al*., 2013].

2.6.4.1 Multi-agent model

MASGriP provides a simulation platform that allows the test and analysis of different types of models, namely energy resource management methodologies, contract negotiation methods, energy transaction models, and diverse types of Demand Response (DR) programs and events. MASGriP multi-agent model is exposed in Figure 2.6.

Players in MASGriP have been implemented to reflect the real world. Operators, such as the Distribution System Operator (DSO) and the Independent System Operator (ISO) have also been included. However, most players represent energy resources such as: different types of consumers (*e.g.* industrial, commercial, residential) and producers (*e.g.* wind farms, solar plants, cogeneration units); EVs with vehicle-to-grid capabilities, among others.

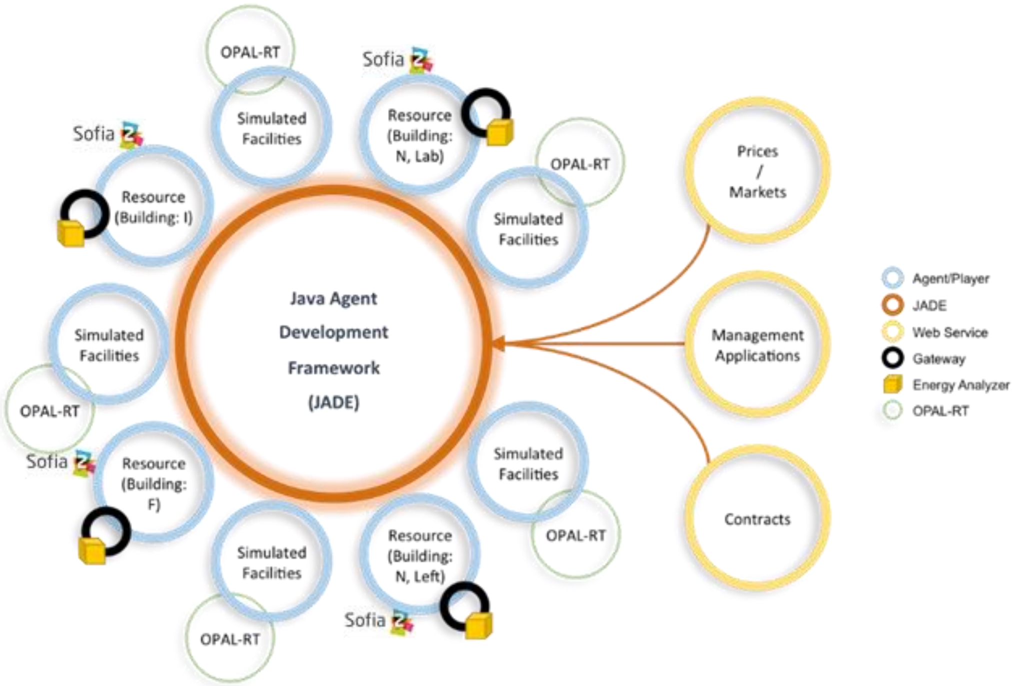


Figure 2.6 - MASGriP multi-agent model, adapted from [Gomes *et al*., 2014b]

2.6.4.2 Physical resources connection

The interface that allows the interaction between real players (humans) and real hardware (loads, generators units, storage systems, etc.) is achieved by using an interface agent that enables the communication with the hardware. Communications are performed using Internet Protocol (IP) to communicate with a Programmable Logic Controller (PLC) and RS-485 to communicate with soft-starters, measurement units, etc.

Each agent has the necessary information to share with the other agents, concerning the type of player, the business model and the contracts being used. The sharing rules can be modified according to negotiations between the players and the aggregators, making MASGriP a dynamic system.

MASGriP is distinguished from other existing simulators due to its features, such as: the inclusion of a large set of different players, the combination of technical and economic treatment of future power systems, the inclusion of both real and simulated players, and the possibility of adding and testing alternative algorithms, such as energy resource management methods, forecasting methodologies, DR models, and negotiation procedures. Its integration with MASCEM allows the simulation platform to go a step further, including the EM simulation capabilities for joint simulations.

MASCEM's distinct types of negotiations, different markets implemented, and types of interactions between the market involved entities in each situation, brought the need for the use of decision support in this simulator. For that purpose a multi-agent based decision support system has arisen. The following subsection provides an overview on the Adaptive Decision Support for Electricity Markets Negotiations (AiD-EM) [Pinto *et al.*, 2015a].

2.6.5 Adaptive Decision Support for Electricity Markets Negotiations

The Adaptive Decision Support for Electricity Markets Negotiations (AiD-EM) [Pinto *et al.*, 2015a] is a multi-agent based decision support system that provides EM players with competitive advantage in the market, enabling a contextual adaptation to the competitors' actions and reactions. Using such decision support solutions, gives players the capability of dealing with the continuous market evolution.

AiD-EM integrates a variety of different decision support solutions, with distinct purposes, which combined altogether contribute to the improvement of the players' performance in EM negotiations.

2.6.5.1 Portfolio optimization

AiD-EM uses a portfolio optimization model for multiple EM participation. In order to maximize its outcomes, the amount of power that a player should negotiate in each available market type is optimized, taking into account the expected prices in each market, in different contexts. The proposed Portfolio Optimization methodology is shown in Figure 2.7.

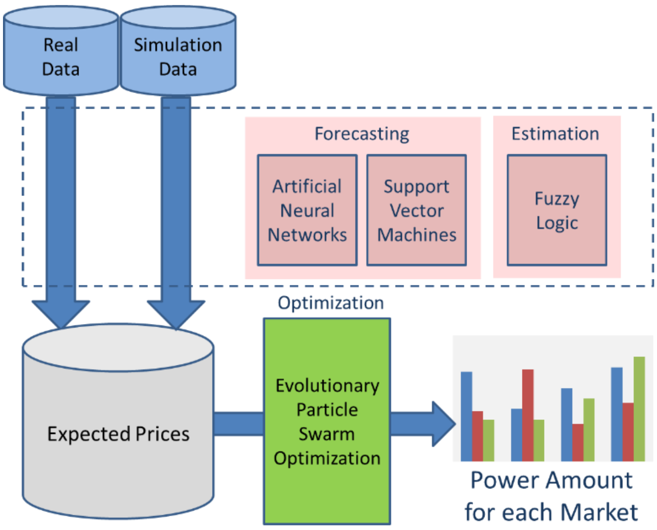


Figure 2.7 - Portfolio Optimization methodology, adapted from [Pinto *et al*., 2015a]

Analysing Figure 2.7 it is possible to observe that the prices forecasts are saved in a database for each market, and each time period of each considered day. The fuzzy logic process determines the ranges of power amount. The prices forecast database is used by the Evolutionary Particle Swarm Optimization (EPSO) meta-heuristic to optimize the participation portfolio in a multi-market environment. Finally, a risk management approach is used, depending on the goals and characteristics of the supported player, the quality of the price forecast, and the decision support execution time constraints. This allows the decision support process to be subjected to different levels of risk.

2.6.5.2 Auction based markets decision support

For the auction based markets decision support, AiD-EM uses Adaptive Learning Strategic Bidding System (ALBidS) [Pinto *et al*., 2013b], [Pinto *et al*., 2014b], which aims at taking the most advantage out of the alternative market strategies that have been introduced in the literature (a rather complete survey about this topic is presented in [David and Wen, 2000]). The general concept behind ALBidS is the integration of as many distinct market strategies as possible, whose performance is evaluated under different contexts of negotiation, and after used by the system to learn which strategies are the most adequate and present the highest chance of success in each different context. Figure 2.8 depicts ALBidS' multi-agent model.

Figure 2.8 - ALBidS multi-agent model [Pinto *et al*., 2013a]

As exposed in Figure 2.8, ALBidS uses reinforcement learning algorithms for the learning process, namely the Roth-Erev algorithm [Roth and Erev, 1995] and an algorithm based on the Bayesian theorem of probability that has been proposed in [Sousa *et al*., 2014]. Additionally, a 2E balance management mechanism has been developed to control the efficiency and effectiveness of the executed algorithms. It allows adapting the execution time of the system to each simulation, *i.e.* if the user wishes to achieve the best results as possible, independently of the execution time, or if the user wishes to get the best results possible in a limited period of time. The 2E balance management mechanism contributes by deciding which tools are used at each moment for each circumstance depending on their observed performance in terms of efficiency and effectiveness.

ALBidS is prepared to deal with different contexts and scenario situations, assuring a large scope of approaches, which offer a greater chance of having suitable responses in very distinct situations. To achieve so, it incorporates a large diversity of market decision support strategies with different natures and perspectives, such as: data mining techniques, forecasting methods, AI methodologies, application of EM directed strategies, mathematic approaches, economic theory based models, and the adaptation of physics theories. Thereby, the system is able to take advantage of the best features of each approach whenever they show to be advantageous.

2.6.5.3 Bilateral contract decision support

Regarding the bilateral contract negotiation, Decision Support for Energy Contracts Negotiation (DECON) [Pinto *et al.*, 2015b] is used: a multi-agent decision support system for bilateral contract negotiations of EM players. It considers the pre-negotiation stage, and also the actual negotiation process. In order to provide as much benefit as possible for the supported player in the undertaken negotiations, the ideal competitor(s) that should be approached are identified by the pre-negotiation decision support. The expected limits and target prices of each targeted competitor are predicted, in order to increase the decision support for the current negotiation. Figure 2.9 presents the pre-negotiation decision support process.

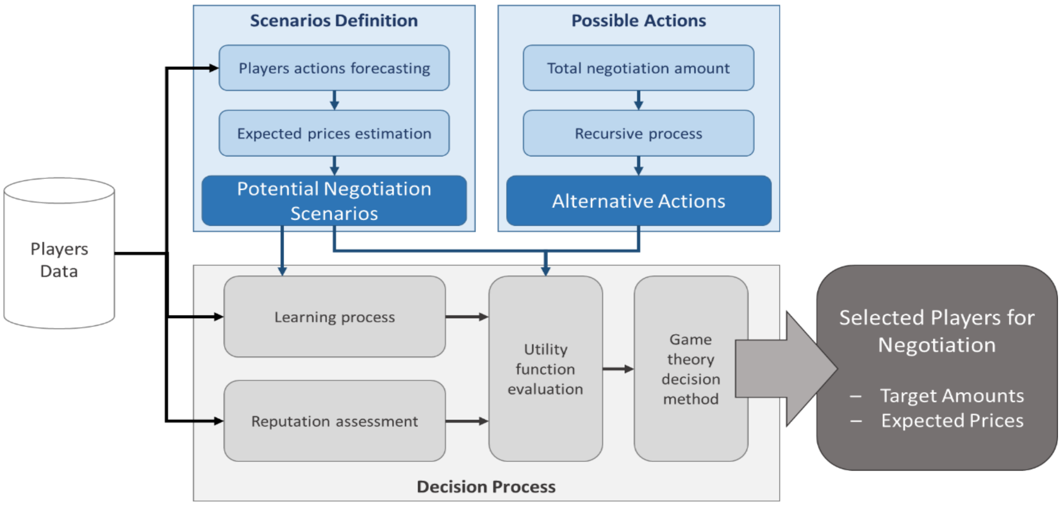


Figure 2.9 - Pre-negotiation decision support process [Pinto *et al.*, 2015b]

As it is possible to observe in Figure 2.9, the game theory concept is applied to allow the analysis of the most likely scenarios to be faced when assuming negotiations. The potential scenarios are based on the opponents' historic data analysis, using forecast methods such as Artificial Neural Networks (ANN) and Support Vector Machine (SVM), among others. The forecasting results are then used by a fuzzy logic process to estimate the expected limit price values of the opponents when negotiating different amounts of power. The expected negotiation prices and the benefit that establishing a contract with one or several players should represent to the supported player is taken into account by using a reputation model. Depending on the risk that the supported player is willing to take, several decision methods are included to allow adaptation, regarding the outcomes of the negotiation process.

The decision support for the actual negotiations consists in a set of different tactics that follow different strategies, where some consider an evolution of the price through time – time-dependent tactics. Behaviour-dependent tactics are also included to determine the changes in prices from one proposal to the following as direct response to the proposals of the competitors. Different tactic combinations are also supported by DECON, allowing the supported player to choose and change its tactic strategically.

2.7 Summary

The EM restructuring process placed several challenges to both enterprises and scientific communities. The sector's rules and operations were changed in order to increase the competitiveness among its participants and provide higher efficiency. To overcome the intrinsic challenges, several simulation tools have arisen, enabling the study of different market models.

The EM can be modelled as a MAS, where each market entity (*i.e.*, buyers, sellers, aggregators, traders, and market and system operators) can be represented by a software agent, with its own knowledge, goals and a certain autonomy. Multi-agent based simulators have proven to be a good option to develop these models, allowing to analyse the market's performance as well as the individual behaviour of each market entity.

In this context, some tools have emerged, confirming the proper application of MAS in the scope of EM study and simulation. Some of the most relevant work in this field has been presented, highlighting main features and limitations. However, none of these tools enables the interaction with other systems, or with heterogeneous agents of similar tools.

Within power engineering, the increasing application of multi-agent technology promotes the adoption of standards that enable the communication between heterogeneous systems, bringing future advantages [McArthur *et al*., 2006], [McArthur *et al*., 2007]. There are several advantages to enable interoperability between tools in the context of the EM, such as: (i) knowledge exchange; (ii) to study, test and/or simulate the participation of a player from a specific market in the context of another market available in other multi-agent based simulator; (iii) to take advantage of decision support tools like AiD-EM, enabling any agent from any multi-gent based simulator to request for support to participate in the simulation of any of the available market types; and (iv) to allow the joint simulation of different markets, from heterogeneous platforms, such as the joint simulation of MASCEM with MASGriP, where a SG from MASGriP can participate in MASCEM's wholesale EM, being seen as a regular player from MASCEM's point of view, and as an aggregator from MASGriP's perspective.

Considering the notorious advantages that the interaction between heterogeneous systems is expected to bring to the power system’s field, particularly to the study of EM, this work had as main goal to enable the interoperability between GECAD's multi-agent simulation platforms and also with externally developed agents. Chapter 3 presents the proposed solution, which includes the development and implementation of ontologies for the interoperability of MAS within the framework of energy systems, contributing to the study, test and simulation of new market models and market entities; and also for the knowledge sharing between heterogeneous power systems' simulation platforms. The proposed ontologies are used by agents for exchanging information, asking questions, and requesting the execution of actions related to their specific domain. The ACL language, proposed by FIPA as a standard for communications between agents, has been used, as the content of its messages includes both the content language and the ontology. The former specifies the syntax, while the latter provides the semantics of the message. This way the correct interpretation of the meaning of the message is assured, removing the ambiguity about the content. The FIPA-SL content language has been used, as it is the only one that reached a stable standard.

In order to enable the required changes, a deep restructuring process of the MASCEM simulator is inevitable. This process has the objective of accommodating the introduction of the required ontologies in GECAD's multi-agent simulation platforms to allow the interoperability between them and with external systems, while turning MASCEM into a FIPA-compliant MAS. This restructuring process has also been performed in the scope of this work and is also presented in detail in chapter 3.

3 Technical Developments

3.1 Introduction

The restructuring turned EM into an attractive domain for software tools developers. Simulation and AI techniques become essential under this context. Multi-agent based simulation is particularly well suited to study and analyse dynamic and adaptive systems with complex interactions between its participating entities. Several multi-agent modelling tools that can be fruitfully applied to the study of restructured wholesale power markets have emerged, as mentioned in section 2.5.

The potential of the integration of different models and platforms brings out the need for communication capabilities that allow entities of different environments (such as software agents) to be able to understand each other and cooperate towards a common goal. The use of ontologies grant the required communication capabilities [FIPA, 2002a] by representing concepts and relationships, defining a common "language" that can be understood by software agents, allowing them to coexist and collaborate.

Since MASCEM was firstly introduced, in 2003 [Praça *et al*., 2003], many changes have occurred in the field of EM. The increase in competitiveness brought by the restructuring process, together with the increasing need to accommodate distributed generation from renewable sources (such as wind and solar generation), the transformation towards the unification of regional markets [EMCC, 2015], [PCR, 2015], the need for an active participation from the consumers side, and the introduction of new paradigms (*e.g.* SGs [SGAM, 2012]) and players (*e.g.* Virtual Power Players [Morais *et al*., 2012]), led to an increasing need for simulation and decision support capabilities that are not easily fulfilled with old and outdated models and architectures.

The following section presents a new version of MASCEM, characterized by an abrupt change in its architecture, aiming at facilitating the integration of new and complementary models, of different natures. The capacity to accommodate different tools and mechanisms is provided by major structural implementation decisions, making MASCEM able to cope with the constant change and highly demanding environment of EM. Implementation decisions such as the use of parallel computing, the careful choice of programming languages for each different algorithm depending on its purpose and requirements, the intelligent distribution of agents by the machines available in the network, the use of heuristic methods when needed, and the integration of a mechanism to manage the balance between the efficiency and effectiveness (2E) of the system.

Furthermore, MASCEM's restructuring is also characterized by the use of ontologies to support players' communications [Santos *et al.*, 2013a], [Santos *et al.*, 2013b], [Santos *et al.*, 2015a], providing the means for an easier cooperation with heterogeneous agent societies, which complement the simulation capabilities of MASCEM. Section 3.3 presents the development and implementation of an EM ontology, representing its main concepts and relationships. The concepts and their relationships are represented in OWL and can be used and extended by each different simulation platform, in a way to integrate different efforts and perspectives. Additionally, ontologies to enable interoperability within different MAS, namely between MASCEM [Praça *et al.*, 2003], [Santos *et al.*, 2015a], [Vale *et al.*, 2011a], AiD-EM [Pinto *et al.*, 2015a] and MASGriP [Oliveira *et al.*, 2012] have also been developed.

The use of languages that can be understood by different systems facilitates the connection and cooperation between them, enabling simulators, such as MASCEM, to integrate several different EM models and power system approaches that allow a broader study capability in this field. Using such common communication language, agents from heterogeneous systems are able to participate in simulations performed by other systems, and use computational models that until now were only available to entities within the same system.

3.2 MASCEM's restructuring

Since its first appearance in 2003, MASCEM has come to accommodate the modelling of a huge number of different players and market types [Santos *et al*., 2015b]. However, with the constant updates, the multi-agent environment has become overly complex, and has uncovered much fragility in the old dated architecture and on the agents' development platform (OAA), which has started to become barely capable of supporting the evolution of the system. For this reason, a complete restructuring has become fundamental, including the re-definition of the multi-agent model, the system's implementation architecture, and the use of proper mechanisms to deal with the highly demanding execution time requirements.

The continuous development of MASCEM has been, and still is, more than ever, crucial for the study and decision support in EM. MASCEM's restructuring aims at optimizing the simulator's performance, providing the means to cope with an evolving complex dynamic reality. Thus, it is possible to provide players with adequate tools to adapt themselves to the new reality, gaining experience to act in the frame of a changing economic, financial, and regulatory environment. The model may be easily enlarged and future evolution of markets may be accomplished with this renewed and enhanced multi-agent simulator. This renovation potentiates the integration of new or updated models and the interconnection with other systems, with their own social environment - which are some of the most important advantages of multi-agent based platforms.

3.2.1 MASCEM's architecture

The definition of MASCEM's global structure has been based on a careful analysis on how the system should behave, both in an independent perspective, and also in what concerns its connection and efficient communication with heterogeneous MAS. For that purpose, it was necessary to take into serious consideration the design of its structure, while at the same time ensuring the best possible performance in what concerns the agents' communications and interoperability.

When re-designing MASCEM, high importance had to be given to defining its architecture, which depends on the characteristics of the system, and will influence all its conception. Choosing the MVC (Model-View-Controller) architecture (Figure 3.1) ensures the independence between the data (model), the user interface (view), and the business layer (controller).

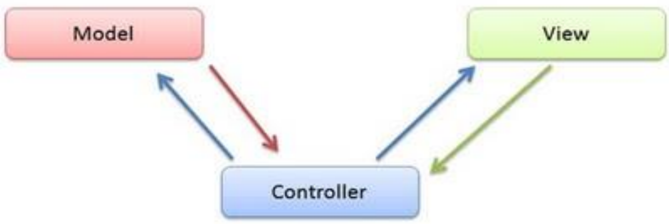


Figure 3.1 - Interaction between the MVC architecture components

A clear separation between the user interface, the data, and the business layer, makes it possible to develop, change, and update each different component independently, without affecting the others; which facilitates the integration of different models and tools that can be easily developed as independent platforms, and then used by MASCEM without the need to make changes to the code. In spite it is still being under development stage, a good example is the graphical user interface that was designed to be automatically loaded at runtime from information stored in a XML file. In addition to being able to be changed at any time without affecting the system's performance, it is also dynamic since a simple redefinition of the XML file content updates the user interface. On the other hand, the user interface is only used when required, such as, for instance, by less experienced users of MASCEM, or for demonstration purposes. Otherwise, if the system's performance should be optimized, the interface can be omitted, reducing the running time. In this case the inputs are loaded from a XML file as well, or from an Excel template file. This culminates in the automatic loading of configurations, which can be altered off-line, facilitating the control of the system.

Restructuring a highly complex system like MASCEM requires the employment of good software engineering practices. Several design patterns have been used [Freeman *et al*., 2004], [Gamma *et al*., 1994], namely some of the original Gang of Four (GoF) design patterns, listed in the book [Gamma *et al*., 1994]. Some examples of the structural patterns used are: (i) the *Adapter*, which allows classes with different interfaces to work together by creating a common object by which they may communicate and interact; and (ii) the *Facade*, which creates a single interface for a set of interfaces within a system. This allows layering systems and subsystems with many dependencies between each other.

Some behavioural design patterns have also been crucial for MASCEM's restructuring, by enabling to take advantage of classes' polymorphism, such as: (i) the *Strategy*, defining a set of encapsulated algorithms that can be swapped to perform a particular behaviour; and (ii) the *Observer*, that allows one or more objects to be notified of status changes in other objects within the system. The *Strategy* is fundamental for the implementation of several alternative bidding strategies. Thus the behaviour of a class (in this case, the desired strategic approach) can be defined at runtime. Moreover, the Observer facilitates the sensing capabilities of the agents within the system, allowing them to perform their actions in the most suitable timings, by being aware of certain changes that occur in other parts of the multi-agent society.

From the creational group of design patterns, the *Factory* has been applied. This pattern provides an interface that delegates the creation calls to other concrete classes in order to return specific objects. The creation of MASCEM's players and market strategies are performed using the implementation of the *Factory* pattern.

Another important feature introduced in MASCEM is its modular architecture. When MASCEM arose, its exponential growth in the several areas that involve the EM was not expected. While trying to follow the EM evolution, MASCEM's code was increasing its size, which made its development more and more complicated over time. With MASCEM's restructuring, it was decided to separate the code into several modules, thus facilitating the continued development of the application and the addition of new modules in the system. The possibility of developing new modules independently from the rest of the application allows to always keep a stable version of the application without obsolete code. Beyond that changes made in each module does not affect the integrity of the remaining components. Figure 3.2 illustrates the main modules of MASCEM's architecture.

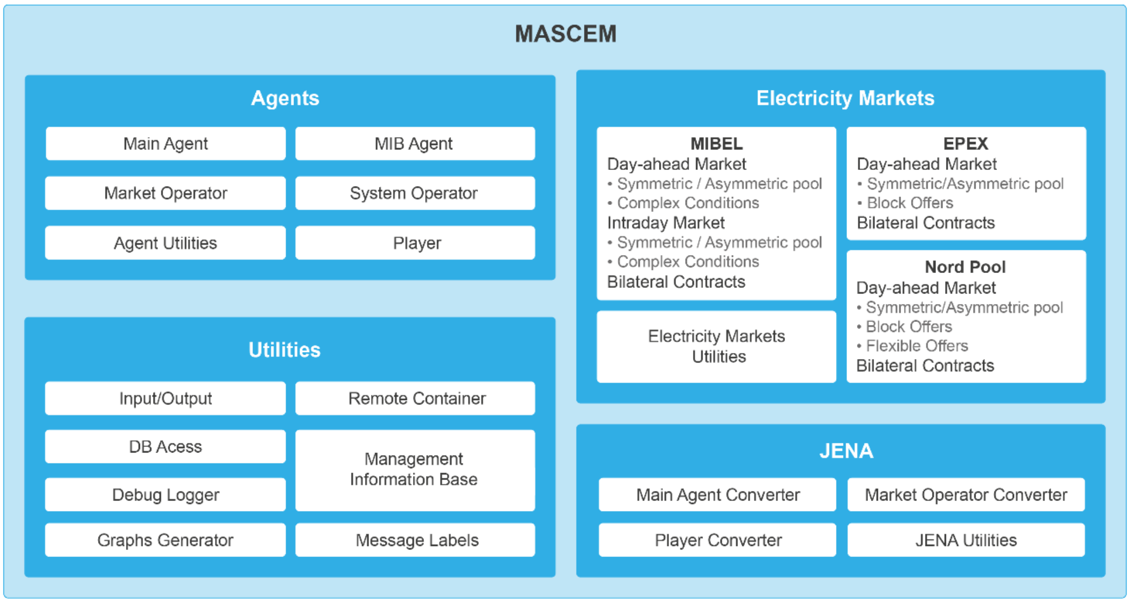


Figure 3.2 - MASCEM's architecture main modules

3.2.2 Multi-agent model

One of the most important outcomes of MASCEM's restructuring process is the compliance with the FIPA standards [FIPA, 2002c], enabling the integration with external agent-based platforms.

FIPA is an IEEE Computer Society standards organization devoted to promote agent-based technology and the interoperability of its standards with other technologies [FIPA, 2014]. MAS using FIPA's standards should be able to interoperate. However, this does not mean that agents are able to exchange any useful information due to the use of different languages and vocabularies, specific of each development platform, domain and developer team.

The Agent Communication Language (ACL) is proposed by FIPA as a standard for communications between agents. Its content includes the content language and the ontology which specify the syntax and the semantics of the message, respectively [FIPA, 2002a]. In this way the ambiguity about the content is removed and the correct interpretation of the message meaning is assured. The FIPA-SL content language is the only one that reached a stable standard. Ontologies are used by agents for exchanging information, asking questions, requesting the execution of actions, and for reasoning.

In order to cope with FIPA's standards, MASCEM communications were changed from the Open Agent Architecture (OAA) framework to the Java Agent Development framework (JADE) [JADE, 2015]. JADE "*is an open source platform for the development of peer-to-peer agent based applications*". It simplifies the implementation of agent-based applications by supporting and complying with FIPA's specifications, through a middle-ware, and also by providing a set of graphical tools to support both debugging and deployment. This way MASCEM is able to interact with agents of other MAS using a common language. However, it is also required that they share a common vocabulary and semantics, so the messages and their contents may be understandable by the agents of each agent society. Ontologies are used to this end, enabling the standardization of communications and interpretation of concepts between independent systems.

MASCEM's multi-agent architecture has been largely expanded in recent years, in order to accommodate the simulation of a diversity of player types [Morais *et al*., 2012], [Pinto *et al*., 2011]. Virtual Power Players (VPPs) represent alliances of small players (small producers, mainly based on distributed generation and renewable sources; and small consumers) that are not able to compete in the market with the big players. VPPs negotiate on the market on behalf of their aggregated players. VPPs also negotiate with their aggregated players when establishing the contracts' conditions, and determining the outcomes of each one, considering the results from the wholesale EM. Initially, VPPs operation was modelled as an independent agents' society within MASCEM's environment.

A large number of small players' types began to be required, such as: electric vehicles, distinct types of production units and consumers (*e.g.* domestic, small commerce, rural consumers, among others).

The large number of players acting in the scope of MASCEM and the inclusion of decision support capabilities with the integration of AiD-EM, meant a huge increase in the complexity of MASCEM's multi-agent model, and consequently a degradation on its execution time. Although each simulation platform (MASCEM's market environment, AiD-EM decision support and VPPs' operation) has been implemented trying to keep them as independent as possible from each other, including the development of specific facilitators to manage each system; the limitations of OAA become insurmountable. The fact of not being FIPA compliant; the limited number of agents per simulation (less than 100); and only allowing to run one facilitator at a time, were some of the reasons that motivated the migration of MASCEM from OAA to JADE.

The transition to JADE facilitated the interoperability with heterogeneous MAS, and eliminated the previous constraints concerning the use of multiple parallel facilitators to manage each independent agent community. This boosted the definitive separation of the MAS, making them more efficient and focused on their purpose, only interacting with each other if intended, thus decreasing the overflow of communications within the system (*i.e.*, OAA is a black board based system where each agent has access to the black board, "answering" only to the messages it can solve; on the other hand, JADE uses peer-to-peer architecture, which eliminates worthless communications since each message is only sent to the specified agents).

MASCEM's multi-agent model has been significantly reduced and simplified by the separation of the MAS and the development of MASGriP – which came to support the simulation of the smaller players that operate at the SG's level. Besides the agents provided by JADE (such as the *AMS* for platform management actions, the *DF* for yellow pages services and the *RMA* for the user interface, among other useful *tool agents*), MASCEM's new version only includes five distinct types of agents, namely:

- Main Agent – enables the user's interaction with the system. It is responsible for starting the market entities from the input file or user's interface; for converting the input data into the respective RDF knowledge bases and for sending them to the respective players and operators; for distributing the various agents by the machines available for the simulation, considering the machines' features and the agents' processing needs; and for properly killing the agents when the user decides to terminate the application;
- MIB Agent – (using the SNMP protocol) it is responsible for reading the management information base of each machine, creating a report and sending it to the Main Agent so that it can decide which agents will move to each machine;
- Market Operator – regulates pool negotiations by validating and analysing the players' bids depending on the type of negotiation, and determines the market price, the accepted and refused bids, and the economical dispatch that will be sent to the system operator;
- System Operator (ISO) – examines the technical feasibility from the power system point of view and solves congestion problems that may arise. It is responsible for the system's security as well as to assure that all conditions are met within the system;
- Player – represents buyer, seller or aggregator agents. On one hand, it may be a consumer or distribution company which participates in the EM in order to buy certain amounts of power. On the other hand, it may simulate electricity producers or other entities able to sell energy in the market, or even aggregations of several entities.

These core agents, very similar to the previous version of MASCEM, allow a simple, yet effective EM simulation. Figure 3.3 presents MASCEM's new multi-agent model.

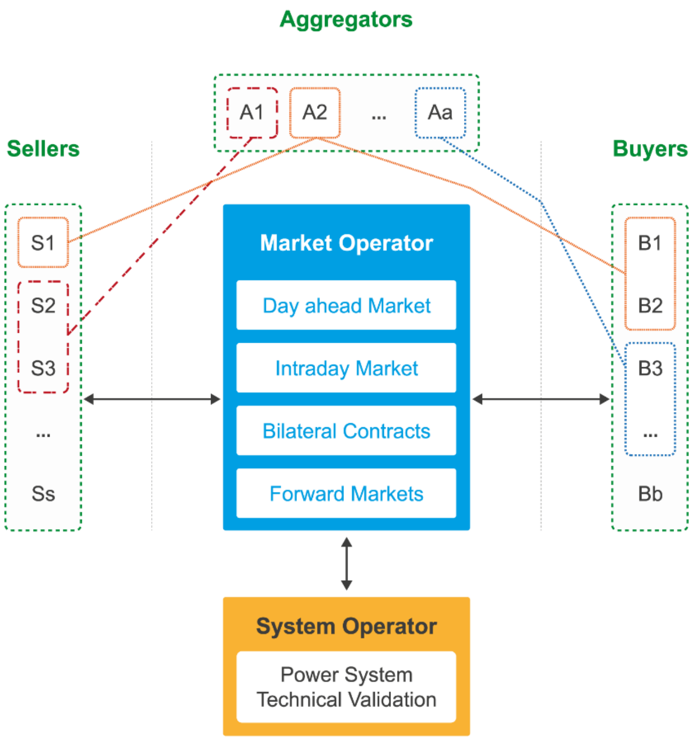


Figure 3.3 - MASCEM's multi-agent model, adapted from [Santos *et al.*, 2015a]

The Buyers, Sellers and Aggregators depicted in Figure 3.3 are only types of market players, and are therefore seen as Player agents from the market's point of view.

The collaboration between the different MAS provides the means to achieve more complex and advanced simulation studies, as shown in Figure 3.4. The core simulation environment provided by MASCEM can be extended by the integration of complementary multi-agent simulators, such as MASGriP or the Aggregators MAS (Figure 3.4).

While MASGriP models and simulates the internal operation of SGs, the Aggregators MAS models the coalition of distributed generation power plants and small consumers (*i.e.* VPPs); and their integration in the EM. The modelling of Aggregators enables the study of new types of negotiations outside the regulatory models present in EM.

Besides being able to participate in MASCEM's electricity market negotiations, players from MASGriP, Aggregators MAS or from other EM multi-agent simulators, are also able to use the decision support capabilities provided by AiD-EM.

MASCEM allows the simulation of several market types: day-ahead and intraday pools (asymmetric or symmetric, with or without complex conditions), bilateral contracts and forward markets. It also enables the simulation of hybrid markets by selecting a combination of the available market models. Other systems may also provide new market types for simulation, such as MASGriP.

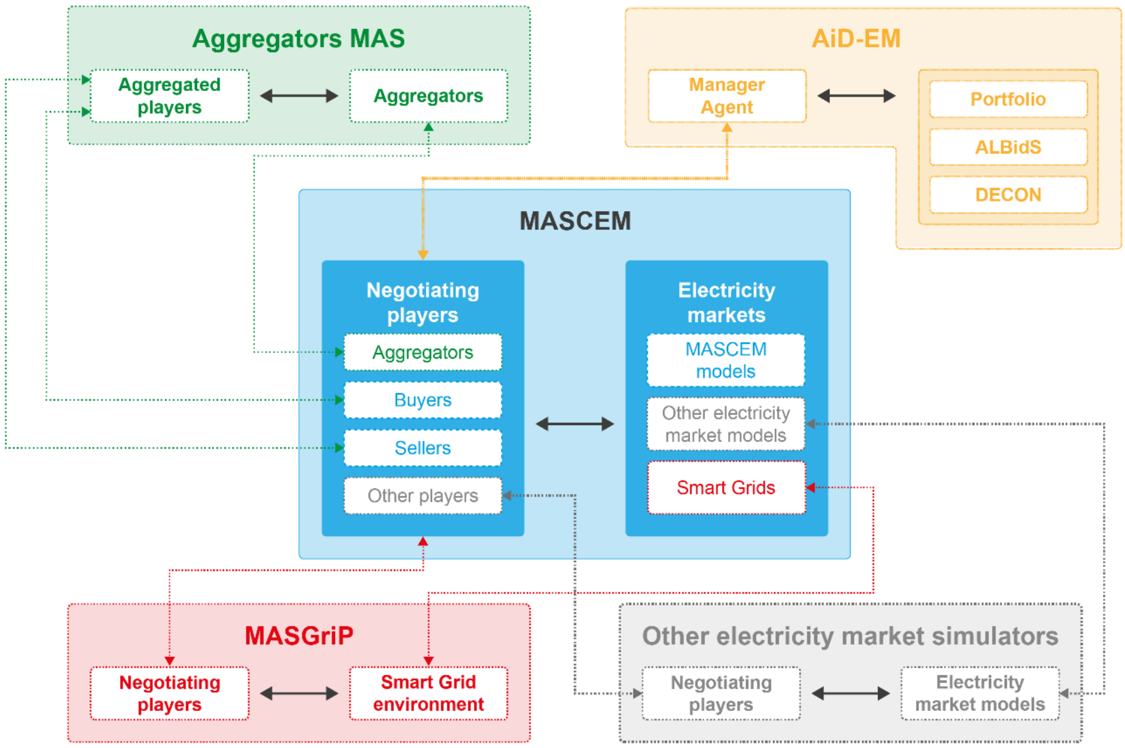


Figure 3.4 - Collaboration between heterogeneous MAS

MASCEM's players are able to participate in SG negotiations through MASGriP. The collaboration between the several agent communities is achieved through the use of ontologies, which define the main concepts that must be understood by agents to participate in power systems and EM related simulations.

Finally, a new concept of simulation has also been introduced in MASCEM. Until now, it was only allowed the simulation of a scenario at a time, since MASCEM only considered one Market Operator agent and one System Operator. With MASCEM's restructuring it was decided to enable the simulation of several scenarios simultaneously, where each scenario has its own agents, *i.e.* the Market Operator, System Operator and Players. Thus, the execution time of the simulations may be optimized and the study and comparison of various simulation scenarios may be simultaneously achieved.

3.2.3 Execution Time Optimization

The variety of algorithms and methods used by MASCEM brings the need to develop a mechanism that is capable of controlling the balance between the system's Efficiency and Effectiveness (2E). The 2E mechanism provides the means to adapt the system's execution time to the purpose of the simulation, *i.e.* if it is intended that the results obtained are the best possible, or if, on the other hand, it is intended that the execution time is limited, once the object of study is other than analysing the performance of the players in the market [Pinto *et al.*, 2014b]. This mechanism manipulates the strategies both externally and internally. It decides which tools are used at each moment for each circumstance, considering the performance in terms of efficiency and effectiveness, by excluding certain strategies when they are not fulfilling the requirements determined for each scenario. The algorithms of the chosen strategies are also manipulated internally, trying to adapt their individual outcomes quality/execution time balance to the needs of each simulation.

The system performance has also been improved by using parallel computing in the data access. Although agents are, by nature, parallel execution entities, there are still times when extra parallelism is required in order to reduce the execution time. The access to huge amounts of data is one of the demanding actions in which parallel computing is used.

A quick exhaustion of the resources of a machine can be led by the huge amount of parallel execution, and for this reason a mechanism that analyses the processing level of each machine available for the simulations, and distributes the agents accordingly, has been implemented. This is the mechanism used by the MIB Agent and Main Agent of MASCEM. The MIB Agent is a remote agent that reads the management information bases of each machine, generating a report that is after sent to the MASCEM's Main Agent. After receiving the report of each machine, the Main Agent redistributes MASCEM's agents by the available machines according to their characteristics and processing needs.

Another important contribution for the optimization of MASCEM's computational efficiency is the use of meta-heuristics, which diminishes the processing time of the required optimizations. Finally, the choice of the most adequate programming language for each of the developed algorithms has also been taken into account. MatLab has been used to implement mathematical calculations, like heuristics and optimization problems; Prolog for logic-based strategies; and C for other time-demanding modules. These developments also come to optimize the performance of the global Java based system, especially taking into account the need to support simulations involving several distinct agents from different simulators, as discussed in section 3.3.

3.3 Ontologies for semantic interoperability

The integration of heterogeneous MAS raises inherent issues to the interconnection of those systems, particularly those involving the use of ontologies independently developed [Dai *et al*., 2013]. These issues need to be addressed in the power industry in order to disseminate the development of interoperable MAS [McArthur *et al*., 2007]. There is a growing need for knowledge exchange between these systems in order to take full advantage of their functionalities. The increasing application of multi-agent technology within power engineering promotes the adoption of standards that enable the communication between heterogeneous systems, bringing future advantages [Catterson *et al*., 2010]. Open standards are needed to provide full interoperability.

Currently, MAS in the power system's domain are developed with their own specific ontologies. These systems share common concepts that are differently represented between the independently developed ontologies, and translating these concepts automatically is not as straightforward as it may seem. FIPA suggests the use of an OA, which provides some related services, to solve the problem of multiple ontologies [FIPA, 2001]. This is still an experimental standard and mappings between ontologies still must be performed by ontologies' designers, which increases the human effort required and costs of implementation.

In alternative, Catterson [Catterson *et al*., 2010] proposes the use of an upper ontology representing the general concepts of the domain, ensuring a common basis for the representation of those concepts and their relationships between systems while reducing the complexity of ontology mapping. However bearing in mind that applications must develop lower-level ontologies for all the application-specific concepts. According to Catterson [Catterson, 2006] there will be no need to modify existing agents when a new system is integrated, if the agents conform to a single upper ontology, as high level concepts would be universally understood, and only these concepts would be discussed. The disadvantage of this approach is that defining high level concepts is a very arduous and complex task, which requires a universal acceptance from all entities involved in the field.

Inspired by this last approach, in [Santos *et al*., 2013a] and [Santos *et al*., 2015a] an upper ontology, containing the main concepts required by the entities that participate in electricity markets and power systems simulators, has been proposed. However, given the constant and rapid evolution of EM, and the consolidation of concepts both at markets' level and also at the conceptual level of top-level ontologies, the original proposed solution has been subject to significant changes.

Considering the definition of upper ontology discussed in subsection 2.4.2, the solution originally suggested in [Santos *et al*., 2013a] of developing an upper ontology for the EM and power systems domain has been dropped. Instead, it was decided to approach the problem from a different, but near perspective.

3.3.1 Ontologies for the interoperability of electricity markets' multi-agent simulation platforms

Rather than developing an "electricity markets and power systems upper ontology", as has been initially considered, this work proposes the development of ontologies for the interoperability of EM multi-agent simulation platforms, which can be extended in a way to enable the full interoperability between those systems. This is the case of the ontologies developed for GECAD's multi-agent based simulators, which is, in fact, the main contribution of this thesis. Figure 3.5 illustrates the ontologies developed in the scope of this work.

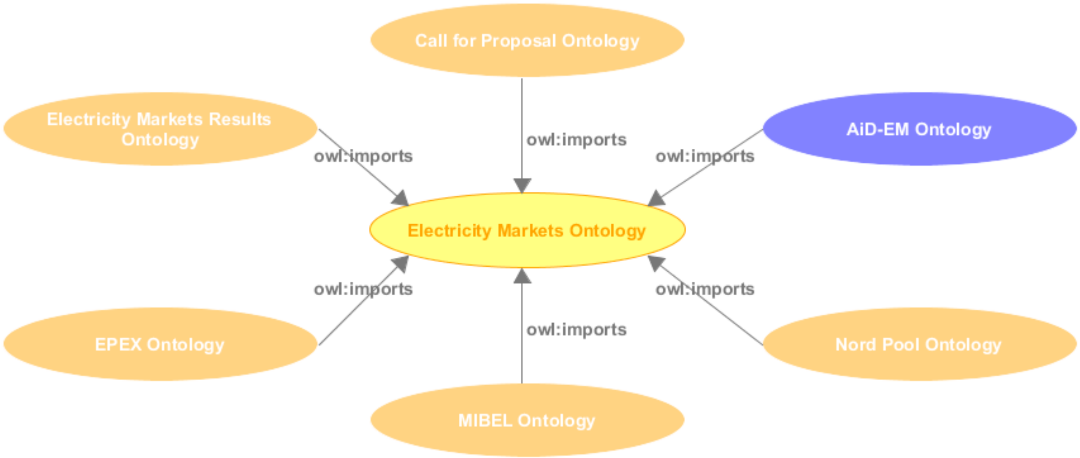


Figure 3.5 - Ontologies for the interoperability of electricity markets' multi-agent simulators

As it is possible to observe in Figure 3.5 the *Electricity Markets Ontology* is the base ontology imported by all the other ontologies. Concepts in this ontology must be abstract enough to be reused and further extended by other ontologies, namely the *EPEX*, *MIBEL* and *Nord Pool* ontologies.

The strategy used to build the ontologies was the "top-down" approach. In this approach the first step is to identify all the relevant concepts, gathering them into a high-level taxonomy and system of axioms, proceeding from there to more specific concepts and axioms; facilitating the task of defining domain-specific content. This is the approach usually applied when the aim is to reuse [Niles and Pease, 2001].

The ontologies have been formulated in OWL DL, using the Protégé[3] tool, and their representation is in RDF/XML. They are publicly available in MASCEM's website[4] so that they can be used by third-party developers who wish to integrate their agent-based simulators with MASCEM, taking advantage of its simulation capabilities and market models; or with AiD-EM which provides decision support in the scope of the EM. On the other hand, the ontologies may also be reused and extended for the development of new multi-agent simulation tools in the context of wholesale EM. The following subsections describe the development of the proposed ontologies.

3.3.1.1 Domain and scope of the ontologies

Before starting developing an ontology it is important to understand the reasons why it is needed. Within this work, the reasons for developing an ontology are:

- for communication: to share a common understanding of EM knowledge domain among software agents, since its main purpose is for the communications held between heterogeneous agent-based simulators;

[3] http://protege.stanford.edu/
[4] http://www.mascem.gecad.isep.ipp.pt/ontologies/

- for computational inference: enabling agents to validate data against the concepts and relationships defined in each ontology;
- for knowledge reuse: to allow agent based systems in the scope of EM, both to enable systems' interoperability, as well as to extend the concepts and relationships to develop the internal communications of independent agent based systems.

When developing an ontology, the first step usually is to define its domain and scope. Within the present work, the domain identified is the wholesale EM domain, and its scope includes the communications to be held between market players and operators in the negotiation processes, not forgetting the AiD-EM's agents providing decision support to market players.

Each EM has rules and clearing price mechanisms taking into account the power systems reality and the available energy mix. Some markets, such as most of the EM in the US [MISO, 2014], have a clearing price mechanism based on the optimization of offers; while others are based on symmetric or asymmetric auctions, as is the case of most European countries. In EU market mechanisms are tending to become more and more alike, in order to ease the accommodation to the unification of these markets.

The three reference EU markets included in MASCEM are: (i) the Iberian market - MIBEL, (ii) the central European market - EPEX and (iii) the northern European market - Nord Pool. Please refer to subsection 2.2.2 for a deeper understanding of the main characteristics of these markets that must be considered in the respective ontologies.

3.3.1.2 Existing ontologies within electricity markets' domain

To reuse existing ontologies is usually a requirement for systems' interoperability. It is almost always worthy to check if someone's work can be extended and refined for our particular domain or task. Even if the ontology is not expressed in the same formalism, knowledge representation systems are usually able to export and import ontologies and translate them from one formalism to another. There are some libraries of reusable ontologies available online, such as Ontolingua[5] and DAML[6] ontology libraries.

It is possible to find in the literature some ontologies developed for the field of energy markets, namely electricity and natural gas [Alexopoulos *et al.*, 2009], [Dam and Chapping, 2010], [Dam and Keirstead, 2010]. Unfortunately none is publicly available for reuse and/or extension, which led to the development from scratch of the ontologies proposed in this thesis.

3.3.1.3 Electricity Markets Ontology

Once the required EM information and market rules present in the various EM available in MASCEM are gathered, the *Electricity Markets Ontology* (EMO)[7] has been developed.

EMO incorporates abstract concepts and axioms referring to the main existing EM. This ontology aims to be as inclusive as possible so that it can be extended and reused in the

[5] http://www.ksl.stanford.edu/software/ontolingua/
[6] http://www.daml.org/ontologies/
[7] http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl

development of (lower level) market-specific ontologies, such as the MIBEL, EPEX, Nord Pool or any other EM ontology. EMO is the base ontology from which all the remaining ontologies developed in the scope of this work are extended. This is also the ontology to extend to define a new market ontology, such as GME (the Italian electricity market) [GME, 2015] to be included in MASCEM or in other simulators.

After determining the domain and scope of the ontology, terms that are transversal to the various EM were identified in order to define the basic concepts for this domain. Figure 3.6 presents the main EM concepts identified and defined as classes in EMO.

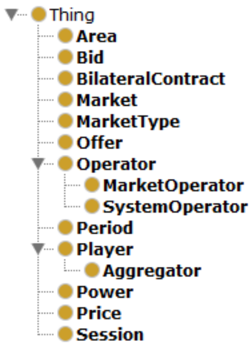


Figure 3.6 - *Electricity Markets Ontology* classes

As it is possible to observe from Figure 3.6, EMO was kept as simple as possible in order to facilitate its reuse and extension independently of the market's features and/or rules. Figure 3.6, thereby identifies the main concepts transversal to global EM. However, given that the suggested ontologies were developed considering its use by agent based simulation tools, some markets' constraints were also defined in EMO, making use of data and object properties, assuring the expected behaviour in newly developed ontologies that import EMO. Figure 3.7 illustrates the object and data properties defined in EMO.

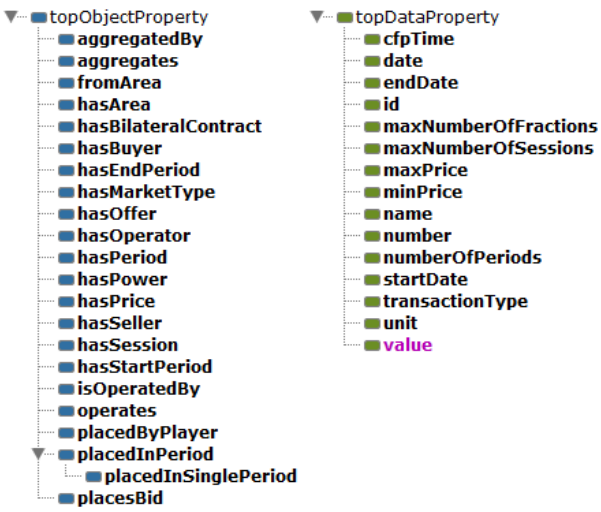


Figure 3.7 - *Electricity Markets Ontology* object and data properties

An *Object Property*, in Protégé, is a property that relates two *Objects* (*i.e. Classes*), while a *Data Property* is a property relating an *Object* to a literal value (*e.g.* string, integer, etc.). In Figure 3.7 the object properties are represented in blue and the data properties in green. Relations between the identified classes and the object and data properties of EMO are illustrated in Figure 3.8.

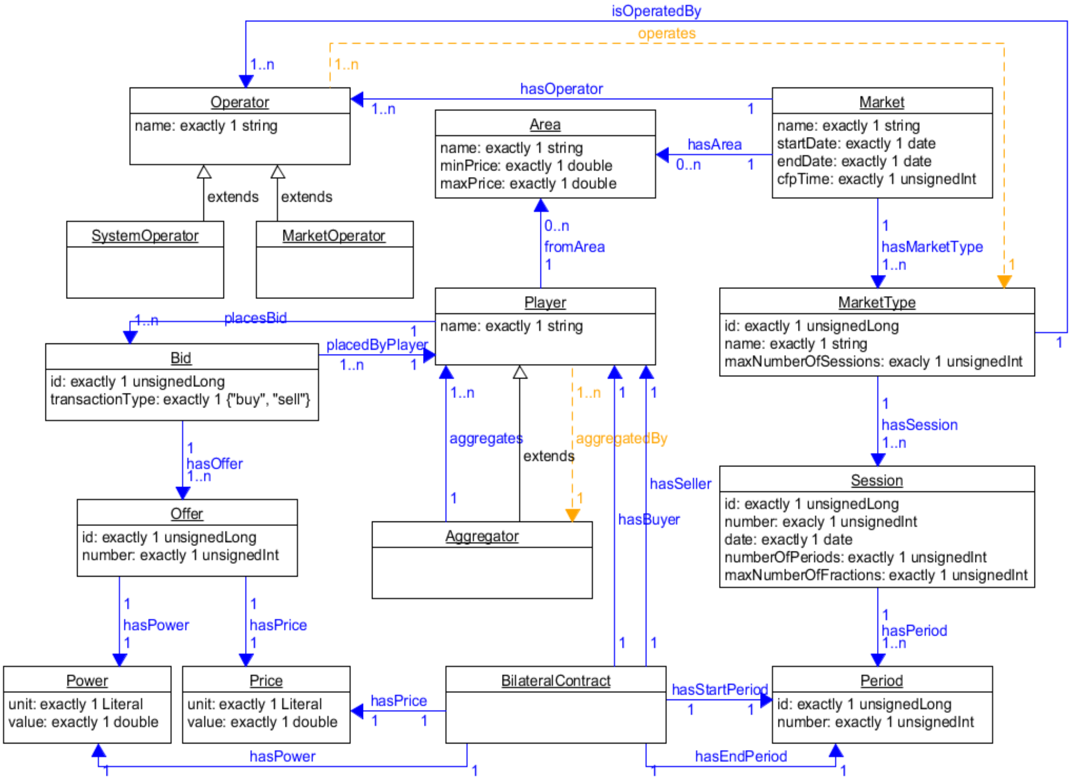


Figure 3.8 - *Electricity Markets Ontology*

From Figure 3.8 it is possible to see the object properties represented in blue and the data properties defined within each class with the respective data types. The orange relations represent the inferred object properties, which are inverse properties of the ones defined in blue in the opposite direction. It should be noticed that three object properties defined in this ontology are not present in the UML diagram, namely: *hasBilateralContract*, *placedInPeriod* and *placedInSinglePeriod*. These are important properties that are introduced in EMO to be reused by the ontologies defined by each EM's domain.

The EMO has expressivity *ALCHIQ(D)* and is defined in description logic (DL) syntax[8]. Table 3.1 presents the object properties, Table 3.2 the data properties and Table 3.3 the classes. The greater the number and variety of concepts that an ontology may represent, the greater is its expressiveness. The *AL* (*Attributive Language*) is the base language allowing: (i) atomic negation, *i.e.* the negation of concept names that do not appear on the left side of axioms; (ii) concept intersection; (iii) universal restrictions; and (iv) limited existential quantification. *C* is

[8] http://www.obitko.com/tutorials/ontologies-semantic-web/owl-dl-semantics.html

the *Complex concept negation* extension. The *H* extension is related with the *role Hierarchy* (*e.g.* the sub properties). The *I* extension represents the *Inverse properties*. The *Q* extension are the *Qualified cardinality restrictions*, *i.e.* cardinality restrictions with fillers other than ⊤. And finally, the *(D)* refers to the use of datatype properties, data values or data types.

Table 3.1 - *Electricity Markets Ontology* object properties DL syntax

Object Properties	
aggregatedBy ⊑ R	hasPower ⊑ R ⊤ ⊑ ≤ 1 hasPower
aggregates ≡ aggregatedBy⁻	hasPrice ⊑ R ⊤ ⊑ ≤ 1 hasPrice
fromArea ⊑ R	hasSeller ⊑ R ⊤ ⊑ ≤ 1 hasSeller
hasArea ⊑ R	hasSession ⊑ R ⊤ ⊑ ≤ 1 hasSession⁻
hasBilateralContract ⊑ R	hasStartPeriod ⊑ R ⊤ ⊑ ≤ 1 hasStartPeriod
hasBuyer ⊑ R ⊤ ⊑ ≤ 1 hasBuyer	isOperatedBy ⊑ R
hasEndPeriod ⊑ R ⊤ ⊑ ≤ 1 hasEndPeriod	operates ≡ isOperatedBy⁻
hasMarketType ⊑ R	placedByPlayer ⊑ R ⊤ ⊑ ≤ 1 placedByPlayer
hasOffer ⊑ R	placesBid ≡ placedByPlayer⁻ ⊤ ⊑ ≤ 1 placesBid⁻
hasOperator ⊑ R	placedInPeriod ⊑ R
hasPeriod ⊑ R ⊤ ⊑ ≤ 1 hasPeriod⁻	placedInSinglePeriod ⊑ placedInPeriod ⊤ ⊑ ≤ 1 placedInSinglePeriod

Table 3.2 - *Electricity Markets Ontology* data properties DL syntax

Data Properties	
cfpTime ⊑ U ⊤ ⊑≤ 1 cfpTime	name ⊑ U ⊤ ⊑≤ 1 name
date ⊑ U ⊤ ⊑ ≤ 1 date	number ⊑ U ⊤ ⊑≤ 1 number
endDate ⊑ U ⊤ ⊑ ≤ 1 endDate	numberOfPeriods ⊑ U
id ⊑ U ⊤ ⊑ ≤ 1 id	startDate ⊑ U ⊤ ⊑ ≤ 1 startDate
maxNumberOfFractions ⊑ U	transactionType ⊑ U ⊤ ⊑ ∀ transactionType.{“buy”, ”sell”}
maxNumberOfSessions ⊑ U	unit ⊑ U ⊤ ⊑ ≤ 1 unit
maxPrice ⊑ U ⊤ ⊑≤ 1 maxPrice	value ⊑ U ⊤ ⊑ ≤ 1 value
minPrice ⊑ U ⊤ ⊑≤ 1 minPrice	

Table 3.3 - *Electricity Markets Ontology* classes DL syntax

Classes
Area ⊑ ⊤ ⊓ 1 name ⊓ 1 maxPrice ⊓ 1 minPrice
Operator ⊑ ⊤ ⊓ 1 name
MarketOperator ⊑ **Operator**
SystemOperator ⊑ **Operator**
Period ⊑ ⊤ ⊓ 1 id ⊓ 1 number
Power ⊑ ⊤ ⊓ 1 unit ⊓ 1 value
Price ⊑ ⊤ ⊓ 1 unit ⊓ 1 value
Offer ⊑ ⊤ ⊓ 1 id ⊓ 1 number ⊓ ∃hasPower 1 **Power** ⊓ ∃hasPrice 1 **Price**
Player ⊑ ⊤ ⊓ 1 name ⊓ ∃fromArea **Area** ⊓ ∃placesBid **Bid**
Aggregator ⊑ **Player** ⊓ ∃aggregates **Player**
Bid ⊑ ⊤ ⊓ 1 id ⊓ 1 transactionType ⊓ ∃placedByPlayer 1 **Player** ⊓ ∃hasOffer **Offer**
Session ⊑ ⊤ ⊓ 1 id ⊓ 1 number ⊓ 1 date ⊓ 1 numberOfPeriods ⊓ 1 maxNumberOfFractions ⊓ ∃hasPeriod **Period**
MarketType ⊑ ⊤ ⊓ 1 id ⊓ 1 name ⊓ 1 maxNumberOfSessions ⊓ ∃hasSession **Session** ⊓ ∃isOperatedBy **Operator**
Market ⊑ ⊤ ⊓ 1 name ⊓ 1 startDate ⊓ 1 endDate ⊓ 1 cfpTime ⊓ ∃hasArea **Area** ⊓ ∃hasMarketType **MarketType** ⊓ ∃hasOperator **Operator**
BilateralContract ⊑ ⊤ ⊓ ∃hasBuyer **Buyer** ⊓ ∃hasSeller **Seller** ⊓ ∃hasStartPeriod **Period** ⊓ ∃hasEndPeriod **Period** ⊓ ∃hasPower **Power** ⊓ ∃hasPrice **Price**
Area ⊓ **Operator** ⊓ **Period** ⊓ **Power** ⊓ **Price** ⊓ **Offer** ⊓ **Player** ⊓ **Bid** ⊓ **Session** ⊓ **Market** ⊓ **MarketType** ⊓ **BilateralContract** = ⊥

The definition of an **Area** includes a string name, a double minPrice and a double maxPrice. All the three data properties are defined as *Functional*. A functional property is a property that only relates the same subject to one single object/value. Each EM area has an identifying name and its minimum and maximum prices are usually defined in its market rules.

An **Operator** includes only a name, while the **MarketOperator** and **SystemOperator** classes are extended from **Operator**. Other types of operators may be present in different EM, which can be defined is each market's ontology after importing the EMO.

A **Period** is here identified only with an id and (period) number. These two properties are both *Functional* as well, and it has been found important to include them in this ontology due to simulation and data storage purposes. It is certain that a period (of time) can also be defined with a start and end instants, but that terminology was left open so that, if required, one can always extend its definition in the ontology by importing EMO.

Both **Price** and **Power** are defined as a set of a unit (*e.g.* EUR and MW respectively) and a value in double, being these two data properties functional as well. An **Offer**, in turn, includes an id, a number and exactly a **Power** and a **Price** set by the object properties hasPower and hasPrice respectively. These two object properties are also *Functional*.

A **Bid** also includes an id, in addition to a transactionType (“*buy*” and “*sell*” only), a single **Player** (set with the *Functional* object property placedByPlayer) and **Offers** (set by the hasOffer object property).

A **Player** includes a name, and identifies its **Area** and placed **Bid**s with the respective object properties fromArea and placesBid. The placesBid object property is the *inverse of* placedByPlayer, being also *Inverse Functional*, *i.e.* this property only relates the same object/value to a single subject. An **Aggregator**, on the other hand, is a subclass of **Player**, which aggregates other **Player**s. The aggregates object property is *inverse of* the aggregatedBy object property, being this last inferred by the reasoner when active.

A **Session** includes an id, a number, a date, the numberOfPeriods and the maxNumberOfFractions data properties, and also the **Period**s. The date data property is *Functional*, the numberOfPeriods identifies the number of periods to consider in the simulation, while the maxNumberOfFractions determines the maximum number of fractions (**Offer**s) per **Bid**. The **Period**s are set with the hasPeriod object property, which is *Inverse Functional*.

The **MarketType** is defined by an id, a name, the maxNumberOfSessions, including its **Session**s and **Operator**s. The maxNumberOfSessions determines the maximum number of sessions to consider in the simulation. The **Session**s and **Operator**s are set with the hasSession and isOperatedBy object properties respectively. The hasSession property is *Inverse Functional* and the isOperatedBy is the *inverse of* operates object property, which is inferred by the reasoner.

A **Market** comprises a name, a startDate, an endDate, a cfpTime, and its **Area**(s), **MarketType**(s) and **Operator**(s). The startDate, endDate and cfpTime properties are *Functional*. The startDate and endDate describe the simulation start and end dates, from which are also determined the number of simulation days. The cfpTime sets the call for proposal time limit a **MarketOperator** will wait to receive the **Player**s’ proposals. The **Area**(s) are set through the hasArea property, the **MarketType**(s) by the hasMarketType property and the **Operator**(s) via the hasOperator object property.

A **BilateralContract** includes a buyer and a seller **Player**, a start and an end **Period**, a **Power** amount and a **Price** offer. The players are set by the hasBuyer and hasSeller *Functional* object properties. The start and end periods by the hasStartPeriod and hasEndPeriod properties respectively, where both are also *Functional*. And the hasPower and hasPrice properties set the **Power** and **Price** respectively.

Finally, the **Area**, the **Operator**, the **Period**, the **Power**, the **Price**, the **Offer**, the **Player**, the **Bid**, the **Session**, the **Market**, the **MarketType** and the **BilateralContract** classes are all *Disjoint Classes*, meaning that none of these classes has members in common. In other words, an element cannot be an instance of more than one of these classes, or else it makes the ontology inconsistent.

The development of EMO has enabled the expansion to the MIBEL, EPEX and Nord Pool ontologies, which are described hereinafter.

3.3.1.4 MIBEL Ontology

The *MIBEL Ontology* (MBL)[9] was the first extension of EMO to be developed. The Iberian market has been the first EM to be implemented in MASCEM and it is in constant development ever since. It is therefore important to keep this ontology as flexible as possible in order to meet its constantly evolving nature.

The MBL ontology imports EMO, extending some of EMO's concepts – namely **Bid**, **Market**, **MarketType** and **Session** – and including the **ComplexConditions** class and subclasses. Figure 3.9 illustrates the classes extended and defined in MBL, highlighted with red rounded rectangles.

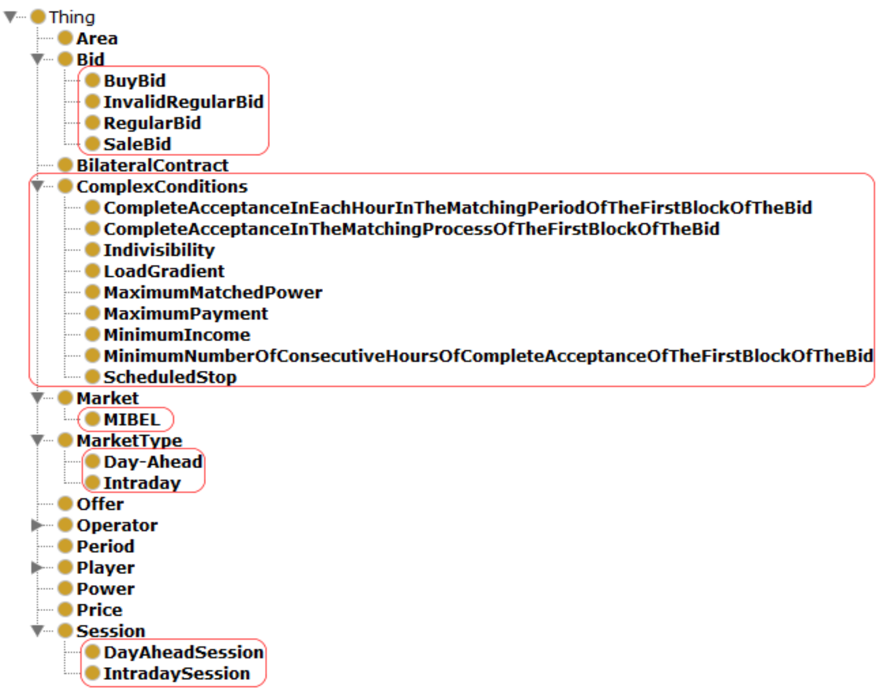


Figure 3.9 - *MIBEL Ontology* classes

As it is possible to observe by Figure 3.9, the concepts **BuyBid**, **InvalidRegularBid**, **RegularBid** and **SaleBid** are extended from **EMO:Bid.** From **EMO:Market** arises the **MIBEL** concept and from **EMO:MarketType** the **Day-Ahead** and **Intraday** subclasses. The **EMO:Session** is super class of **DayAheadSession** and **IntradaySession**. The **ComplexConditions** object is included as a new concept together with its particular subclasses, namely: **CompleteAcceptanceInEachHourInTheMatchingPeriodOfTheFirstBlockOfTheBid**, **CompleteAcceptanceInTheMatchingProcessOfTheFirstBlockOfTheBid**, **Indivisibility**, **LoadGradient**, **MaximumMatchedPower**, **MaximumPayment**, **MinimumIncome**, **MinimumNumberOfConsecutiveHoursOfCompleteAcceptanceOfTheFirstBlockOfTheBid** and **ScheduledStop**, representing the different types of complex conditions available in the Iberian market.

[9] http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl

MBL also includes new object and data properties with respect to the complex conditions. Figure 3.10 features the new object and data properties included in MBL.

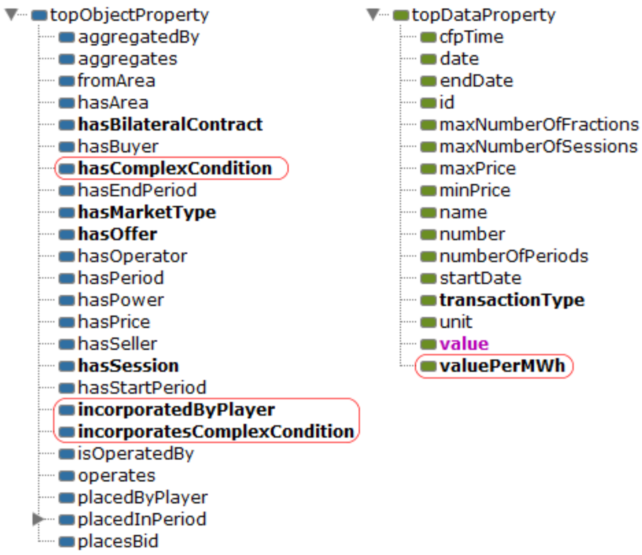


Figure 3.10 - *MIBEL Ontology* object and data properties

On the left part of Figure 3.10, the new object properties are highlighted, namely the **hasComplexCondition**, **incorporatedByPlayer** and **incorporatesComplexCondition**; and on the right part the new data property **valuePerMWh** is highlighted. All these new properties are related to the new concept of **ComplexConditions** and will be further explained hereinafter.

The MBL ontology is illustrated in Figure 3.11 where the classes, object properties and data property identified above are represented. The existing relations between them and between them and the EMO's concepts and properties are also shown.

The yellow rectangles represent the concepts imported from EMO. In blue are the object properties. If imported from EMO they use the prefix "EMO:". The inferred object property **incorporatesComplexCondition**, which is an inverse property of **incorporatedByPlayer** is represented in orange. The relations between the remaining EMO concepts have been left out in order to simplify the reading of the diagrams, since they have already been presented in subsection 3.3.1.3.

From Figure 3.11 it is possible to observe that the different complex conditions are distributed between the distinct market types. Both market types have different constraints in MIBEL, depending on if it is a day-ahead or intraday session. On the other hand, MIBEL only makes available one type of **Bid**, the **RegularBid** which can only be placed in one **EMO:Period** (placedInSinglePeriod data property) and contain a maximum of 25 **EMO:Offer**s. **BuyBid** and **SaleBid** are types of bids inferred depending on their transactionType data property, while an **InvalidRegularBid** represents a **Bid** with more than 25 fractions (**EMO:Offer**).

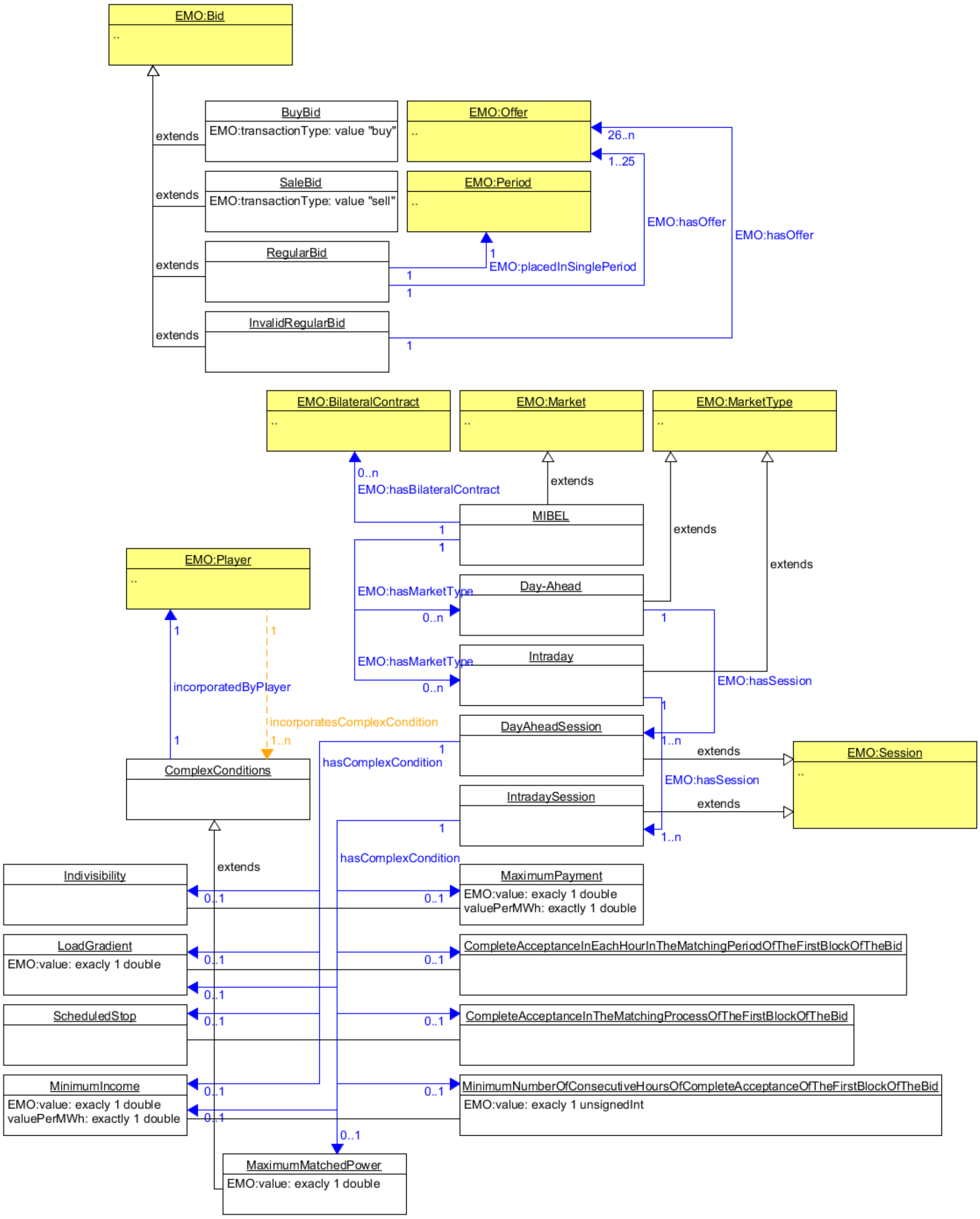


Figure 3.11 - *MIBEL Ontology*

This ontology is used both by players and by the market operator. The market operator detains a knowledge base defining the market's features. This knowledge base is created from the user's input file. The same input file also determines the players' knowledge bases. The market operator gathers the players' proposals using the ontology's conceptualization.

The MBL ontology expressivity is the same of EMO: *ALCHIQ(D)*. Table 3.4, Table 3.5 and Table 3.6 present the object properties, data property and classes of the MBL ontology in DL syntax, respectively.

Table 3.4 - *MIBEL Ontology* object properties DL syntax

Object Properties	
hasComplexCondition ⊑ R	incorporatesComplexCondition ≡ incorporatedByPlayer⁻ ⊤ ⊑ ≤ 1 incorporatesComplexCondition⁻
incorporatedByPlayer ⊑ R ⊤ ⊑ ≤ 1 incorporatedByPlayer	

Table 3.5 - *MIBEL Ontology* data property DL syntax

Data Property
valuePerMWh ⊑ U ⊤ ⊑≤ 1 valuePerMWh

Table 3.6 - *MIBEL Ontology* classes DL syntax

Classes
BuyBid ⊑ **EMO:Bid** ⊓ EMO:transactionType "buy"
SaleBid ⊑ **EMO:Bid** ⊓ EMO:transactionType "sell"
RegularBid ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer ≤ 25 **EMO:Offer** ⊓ ∃EMO:placedInSinglePeriod 1 **EMO:Period**
InvalidRegularBid ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer ≥ 26 **EMO:Offer**
ComplexConditions ⊑ ⊤ ⊓ ∃incorporatedByPlayer 1 **EMO:Player**
CompleteAcceptanceInEachHourInTheMatchingPeriodOfTheFirstBlockOfTheBid ⊑ **ComplexConditions**
CompleteAcceptanceInTheMatchingProcessOfTheFirstBlockOfTheBid ⊑ **ComplexConditions**
Indivisibility ⊑ **ComplexConditions**
LoadGradient ⊑ **ComplexConditions** ⊓ 1 EMO:value
MaximumMatchedPower ⊑ **ComplexConditions** ⊓ 1 EMO:value
MaximumPayment ⊑ **ComplexConditions** ⊓ 1 EMO:value ⊓ 1 valuePerMWh
MinimumIncome ⊑ **ComplexConditions** ⊓ 1 EMO:value ⊓ 1 valuePerMWh
MinimumNumberOfConsecutiveHoursOfCompleteAcceptanceOfTheFirstBlockOfTheBid ⊑ **ComplexConditions** ⊓ 1 EMO:value
ScheduledStop ⊑ **ComplexConditions**
DayAheadSession ⊑ **EMO:Session** ⊓ ∃hasComplexCondition ≤ 1 **Indivisibility** ⊓ ∃hasComplexCondition ≤ 1 **LoadGradient** ⊓ ∃hasComplexCondition ≤ 1 **MinimumIncome** ⊓ ∃hasComplexCondition ≤ 1 **ScheduledStop**
IntradaySession ⊑ **EMO:Session** ⊓ ∃hasComplexCondition ≤ 1 (**MaximumPayment** ⊔ **MinimumIncome**) ⊓ ∃hasComplexCondition ≤ 1 **CompleteAcceptanceInEachHourInTheMatchingPeriodOfTheFirstBlockOfTheBid** ⊓ ∃hasComplexCondition ≤ 1 **CompleteAcceptanceInTheMatchingProcessOfTheFirstBlockOfTheBid** ⊓ ∃hasComplexCondition ≤ 1 **LoadGradient** ⊓ ∃hasComplexCondition ≤ 1

MaximumMatchedPower ⊓ ∃hasComplexCondition ≤ 1 **MinimumNumberOfConsecutiveHoursOfCompleteAcceptanceOfTheFirstBlockOfTheBid**
Day-Ahead ⊑ **EMO:MarketType** ⊓ ∃EMO:hasSession **DayAheadSession**
Intraday ⊑ **EMO:MarketType** ⊓ ∃EMO:hasSession **IntradaySession**
MIBEL ⊑ **EMO:Market** ⊓ ∃EMO:hasMarketType **Day-Ahead** ⊓ ∃EMO:hasMarketType **Intraday** ⊓ ∃EMO:hasBilateralContract **EMO:BilateralContract**
ComplexConditions ⊓ **EMO:Area** ⊓ **EMO:Operator** ⊓ **EMO:Period** ⊓ **EMO:Power** ⊓ **EMO:Price** ⊓ **EMO:Offer** ⊓ **EMO:Player** ⊓ **EMO:Bid** ⊓ **EMO:Session** ⊓ **EMO:Market** ⊓ **EMO:MarketType** ⊓ **EMO:BilateralContract** = ⊥

BuyBid and **SaleBid** are subclasses of **EMO:Bid** being defined by the transactionType data property, which is equal to “buy” or “sell” respectively. A **RegularBid** is also a subclass of **EMO:Bid** but including a maximum number of 25 **EMO:Offer**s using the object property EMO:hasOffer. It can only be related to an **EMO:Period**, making use of the EMO:placedInSinglePeriod *Functional* object property. On the other hand, an **InvalidRegularBid** in MLB ontology is defined as a **EMO:Bid** with more than 25 **EMO:Offer**s.

The **ComplexConditions** concept includes the **EMO:Player** that places the constraints with the object property incorporatedByPlayer. The **Indivisibility**, the **ScheduledStop**, the **CompleteAcceptanceInEachHourInTheMatchingPeriodOfTheFirstBlockOfTheBid** and the **CompleteAcceptanceInTheMatchingProcessOfTheFirstBlockOfTheBid** are subclasses of **ComplexConditions**. The **LoadGradient**, the **MaximumMatchedPower**, and the **MinimumNumberOfConsecutiveHoursOfCompleteAcceptanceOfTheFirstBlockOfTheBid** are also subclasses of **ComplexConditions** but include a EMO:value data property which can be a double value in the case of the first two conditions (representing the load amount) or an integer in the case of the last (representing the number of hours). The remaining complex conditions, *i.e.* **MaximumPayment** and **MinimumIncome**, in addition to being subclasses of **ComplexCondition** and including the EMO:value data property, are also defined by a valuePerMWh data property.

A **DayAheadSession** is subclass of **EMO:Session** and may include one or more of the complex conditions: **Indivisibility**, **LoadGradient**, **MinimumIncome** and **ScheduledStop**, using the object property hasComplexCondition. A **IntradaySession** is also subclass of **EMO:Session** and may include one or more of the following conditions: **MaximumPayment** or **MinimumIncome** (depending on being a buyer or seller agent respectively), **LoadGradient**, **MaximumMatchedPower**, **CompleteAcceptanceInEachHourInTheMatchingPeriodOfTheFirst-BlockOfTheBid**, **CompleteAcceptanceInTheMatchingProcessOfTheFirstBlockOfTheBid** and **MinimumNumberOfConsecutiveHoursOfCompleteAcceptanceOfTheFirstBlockOfTheBid**.

The **Day-Ahead** and **Intraday** concepts are subclasses of **EMO:MarketType**, including the **DayAheadSession** and **IntradaySession** respectively, making use of the EMO:hasSession object property.

MIBEL is subclass of **EMO:Market** including the **Day-Ahead** and **Intraday** market types and also the **EMO:BilateralContract**, using EMO:hasMarketType and EMO:hasBilateralContract object properties respectively.

Finally, the **ComplexConditions**, the **EMO:Area**, the **EMO:Operator**, the **EMO:Period**, the **EMO:Power**, the **EMO:Price**, the **EMO:Offer**, the **EMO:Player**, the **EMO:Bid**, the **EMO:Session**, the **EMO:Market**, the **EMO:MarketType** and the **EMO:BilateralContract** classes are all Disjoint Classes.

3.3.1.5 EPEX Ontology

EPEX and Nord Pool markets are very similar, however their ontologies are independent to accomplish with the fast evolution of EM, which may bring differences between both.

The *EPEX Ontology* (EPX)[10] imports EMO, extending its concepts and including some new data properties. Figure 3.12 highlights the classes and data properties included in EPX.

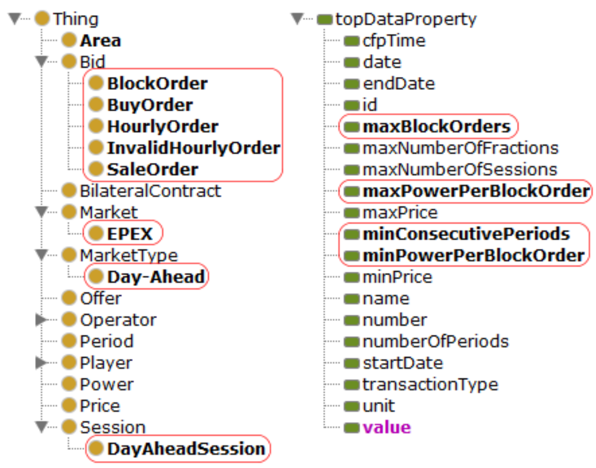


Figure 3.12 - *EPEX Ontology* classes and data properties

EPX ontology extends only concepts from EMO. The **BuyOrder**, the **SaleOrder**, the **HourlyOrder** and the **InvalidHourlyOrder** are analogous to the **MBL:BuyBid**, **MBL:SaleBid**, **MBL:RegularBid** and **MBL:InvalidRegularBid** respectively, in the MBL ontology; as well as the concepts extended from **EMO:Market**, **EMO:MarketType** and **EMO:Session**. The novelty here is the **BlockOrder** which can be seen as similar to a MIBEL complex condition.

The classes, the object properties and data properties defined in EPX are shown in Figure 3.13.

EMO's classes are presented in yellow, while its data and object properties have the prefix "EMO:". As can be seen by Figure 3.13, the **EMO:Area** is redefined in EPX, including the new four data properties of EPX.

[10] http://www.mascem.gecad.isep.ipp.pt/ontologies/epex.owl

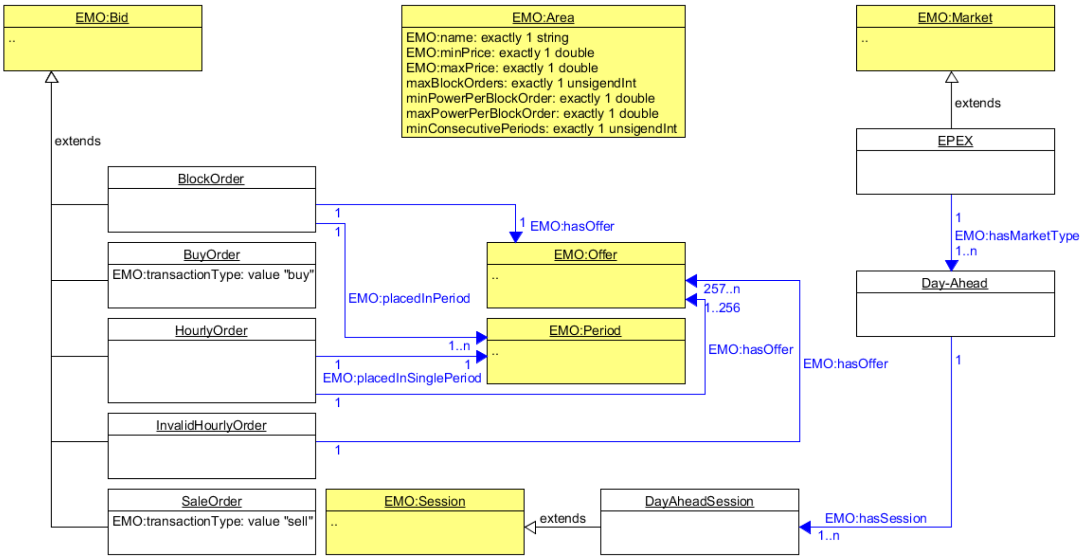


Figure 3.13 - *EPEX Ontology*

This ontology is used by players participating in the EPEX market and its market operator, in the same way as the MBL ontology.

The EPX ontology data properties and classes DL syntaxes are presented in Table 3.7 and Table 3.8 respectively. Its expressivity is the same as EMO too: *ALCHIQ(D)*.

Table 3.7 - *EPEX Ontology* data properties DL syntax

Data Properties	
maxBlockOrders ⊑ U ⊤ ⊑≤ 1 maxBlockOrders	minPowerPerBlockOrder ⊑ U ⊤ ⊑≤ 1 minPowerPerBlockOrder
maxPowerPerBlockOrder ⊑ U ⊤ ⊑≤ 1 maxPowerPerBlockOrder	minConsecutivePeriods ⊑ U ⊤ ⊑≤ 1 minConsecutivePeriods

Table 3.8 - *EPEX Ontology* classes DL syntax

Classes
Area ⊑ **EMO:Area** ⊓ 1 maxBlockOrders ⊓ 1 maxPowerPerBlockOrder ⊓ 1 minPowerPerBlockOrder ⊓ 1 minConsecutivePeriods
BuyOrder ⊑ **EMO:Bid** ⊓ EMO:transactionType "buy"
SaleOrder ⊑ **EMO:Bid** ⊓ EMO:transactionType "sell"
BlockOrder ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer 1 **EMO:Offer** ⊓ ∃EMO:placedInPeriod **EMO:Period**
HourlyOrder ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer ≤ 256 **EMO:Offer** ⊓ ∃EMO:placedInSinglePeriod 1 **EMO:Period**
InvalidHourlyOrder ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer ≥ 257 **EMO:Offer**
DayAheadSession ⊑ **EMO:Session**
Day-Ahead ⊑ **EMO:MarketType** ⊓ ∃EMO:hasSession **DayAheadSession**
EPEX ⊑ **EMO:Market** ⊓ ∃EMO:hasMarketType **Day-Ahead**

An **Area** is here redefined to include new data properties that relate to the EPEX electricity market, namely maxBlockOrders, maxPowerPerBlockOrder, minPowerPerBlockOrder and minConsecutivePeriods. Each area in EPEX determines these values considering its particular constraints. On the other hand, enabling a greater flexibility of parameterizations enables more valuable and richer simulations.

BuyOrder and **SaleOrder** are subclasses of **EMO:Bid,** being defined by the transactionType data property, which is equal to "buy" or "sell" respectively. **BlockOrder** is also subclass of **EMO:Bid** but only comprises an **EMO:Offer** valid for an interval of **EMO:Periods**, using the EMO:hasOffer and EMO:placedInPeriod respectively. The **HourlyOrder** is another subclass of **EMO:Bid** but including a maximum number of 256 **EMO:Offer**s; and it only can be related to a **EMO:Period**, making use of the EMO:placedInSinglePeriod *Functional* object property. On the other hand, an **InvalidHourlyOrder** in EPX ontology is defined as a **EMO:Bid** with more than 256 **EMO:Offer**s.

DayAheadSession is subclass of **EMO:Session**; and the **Day-Ahead** is subclass of **EMO:MarketType**, including the **DayAheadSession** using the object property EMO:hasSession. The **EPEX** concept is subclass of **EMO:Market** and includes the **Day-Ahead** market type with the object property EMO:hasMarketType.

3.3.1.6 Nord Pool Ontology

The *Nord Pool Ontology* (NPO)[11] is very similar to the EPX, as mentioned above. The classes, object property and data properties included in NPO are highlighted in Figure 3.14.

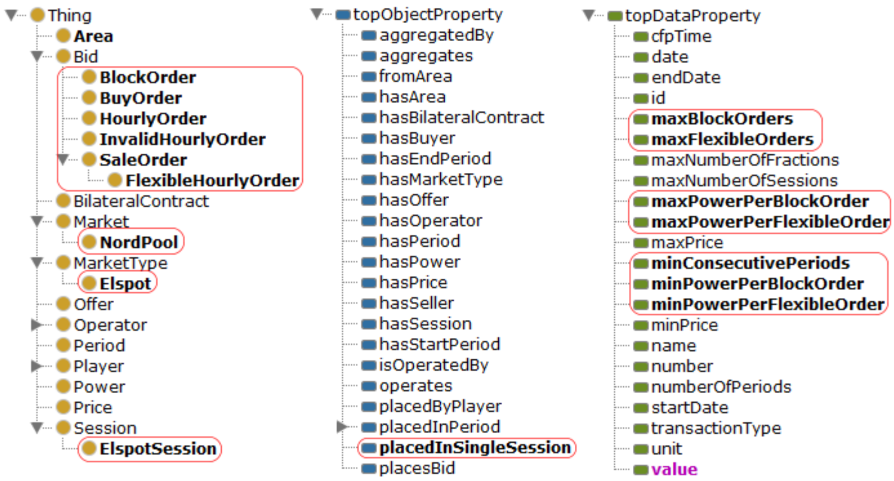


Figure 3.14 - *Nord Pool Ontology* classes, object and data properties

The main difference between NPO and EPX is related to the inclusion of the flexible hourly orders. As it is possible to observe by Figure 3.14, the **FlexibleHourlyOrder** concept (on the left column) is included as a subclass of **EMO:SaleOrder**, meaning that it is only allowed as a sale bid. It is also visible the inclusion of a new object property – placedInSinglePeriod – and three new data properties: maxFlexibleOrders, maxPowerPerFlexibleOrder and minPowerPerFlexibleOrder. The **FlexibleHourlyOrder** of NPO may also be seen as a complex

[11] http://www.mascem.gecad.isep.ipp.pt/ontologies/nordpool.owl

condition only available for sellers, similarly to the day-ahead complex conditions of MIBEL, which are only allowed for seller agents.

The **NordPool**, **Elspot** and **ElspotSession** classes of NPO are analogous to the **EPX:EPEX**, **EPX:Day-Ahead** and **EPX:DayAheadSession** of the *EPEX Ontology*.

Figure 3.15 exposes the classes, object properties and data properties of NPO.

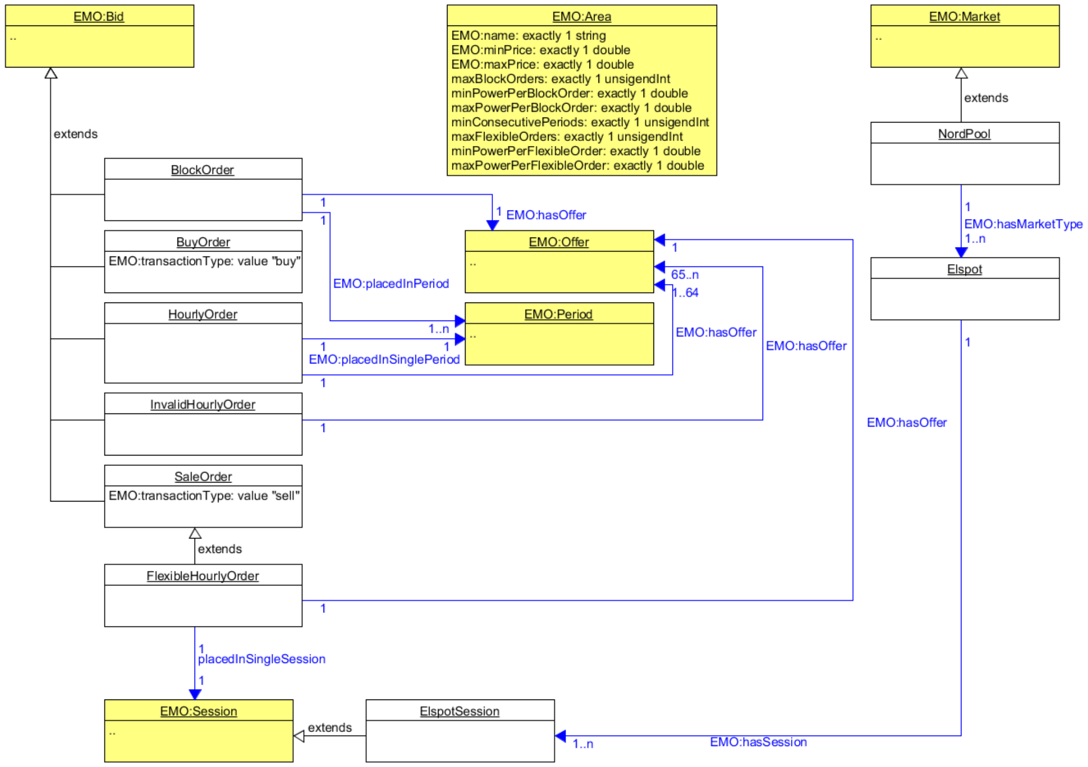


Figure 3.15 - *Nord Pool Ontology*

The EMO's concepts are illustrated in yellow, and the prefix "EMO:" identifies EMO's object and data properties. The object properties of both EMO and NPO are identified in blue.

In NPO, the **EMO:Area** includes the three new added data properties, besides the ones also included in EPX. Another point to take into consideration is the **FlexibleHourlyOrder** which can only be placed in one single session.

Similarly to MBL and EPX ontologies, NPO is used by market players willing to participate in **Elspot** through its market operator. NPO has also *ALCHIQ(D)* expressivity and its object property, data properties and classes DL syntaxes are provided in Table 3.9, Table 3.10 and Table 3.11.

Table 3.9 - *Nord Pool Ontology* object property DL syntax

Object Property
placedInSingleSession $\sqsubseteq R$
$\top \sqsubseteq \leq 1$ placedInSingleSession

Table 3.10 - *Nord Pool Ontology* data properties DL syntax

Data Properties	
maxBlockOrders ⊑ U ⊤ ⊑≤ 1 maxBlockOrders	maxFlexibleOrders ⊑ U ⊤ ⊑≤ 1 maxFlexibleOrders
maxPowerPerBlockOrder ⊑ U ⊤ ⊑≤ 1 maxPowerPerBlockOrder	maxPowerPerFlexibleOrder ⊑ U ⊤ ⊑≤ 1 maxPowerPerFlexibleOrder
minPowerPerBlockOrder ⊑ U ⊤ ⊑≤ 1 minPowerPerBlockOrder	minPowerPerFlexibleOrder ⊑ U ⊤ ⊑≤ 1 minPowerPerFlexibleOrder
minConsecutivePeriods ⊑ U ⊤ ⊑≤ 1 minConsecutivePeriods	

Table 3.11 - *Nord Pool Ontology* classes DL syntax

Classes
Area ⊑ **EMO:Area** ⊓ 1 maxBlockOrders ⊓ 1 maxPowerPerBlockOrder ⊓ 1 minPowerPerBlockOrder ⊓ 1 minConsecutivePeriods ⊓ 1 maxFlexibleOrders ⊓ 1 maxPowerPerFlexibleOrder ⊓ 1 minPowerPerFlexibleOrder
BuyOrder ⊑ **EMO:Bid** ⊓ EMO:transactionType "buy"
SaleOrder ⊑ **EMO:Bid** ⊓ EMO:transactionType "sell"
BlockOrder ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer 1 **EMO:Offer** ⊓ ∃EMO:placedInPeriod **EMO:Period**
HourlyOrder ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer ≤ 64 **EMO:Offer** ⊓ ∃EMO:placedInSinglePeriod 1 **EMO:Period**
InvalidHourlyOrder ⊑ **EMO:Bid** ⊓ ∃EMO:hasOffer ≥ 65 **EMO:Offer**
FlexibleOrder ⊑ **SaleOrder** ⊓ ∃EMO:hasOffer 1 **EMO:Offer** ⊓ ∃EMO:placedInSingleSession 1 **EMO:Session**
ElspotSession ⊑ **EMO:Session**
Elspot ⊑ **EMO:MarketType** ⊓ ∃EMO:hasSession **ElspotSession**
NordPool ⊑ **EMO:Market** ⊓ ∃EMO:hasMarketType **Elspot**

An **Area** in NPO is redefined to include the data properties maxBlockOrders, maxPowerPerBlockOrder, minPowerPerBlockOrder, minConsecutivePeriods, maxFlexibleOrders, maxPowerPerFlexibleOrder, minPowerPerFlexibleOrder. Similarly to EPEX, each area determines these values considering its constraints.

BuyOrder, **SaleOrder** and **BlockOrder** are defined in the same way of the EPX ontology. The **HourlyOrder** is subclass of **EMO:Bid** including a 64 **EMO:Offer**s limit, and it can only be relative to a single **EMO:Period** too, like in EPX, making use of the same object property: EMO:placedInSinglePeriod. In turn, an **InvalidHourlyOrder** in NPO ontology is defined as a **EMO:Bid** with more than 64 **EMO:Offer**s.

An **ElspotSession** is subclass of **EMO:Session**; and the **Elspot** is subclass of **EMO:MarketType**, including the **ElspotSession** using the object property EMO:hasSession. The **NordPool** concept is subclass of **EMO:Market** and includes the **Elspot** market type with the object property EMO:hasMarketType.

3.3.1.7 Call For Proposal Ontology

After the development of each market's specific ontology (*i.e.* MIBEL, EPEX and Nord Pool), and taking advantage of the already acquired knowledge, the *Call For Proposal* (CFP)[12] ontology has been developed. The CFP has the purpose of being used by the Market Operator agents to ask players for bids to be placed in the market.

The CFP ontology imports EMO and extends it by including two new classes, namely the **CallForProposal** and the **Proposal**; and a new object property: forElectricityMarket. Figure 3.16 shows the classes and object property defined in CFP.

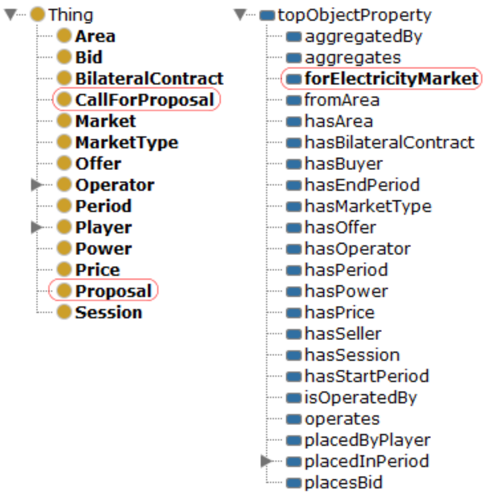


Figure 3.16 - *Call For Proposal Ontology* classes and object property

On the left side of Figure 3.16 (in yellow), the new included classes are highlighted in red. On the right side (in blue), the new object property is also highlighted with a red ellipse. Figure 3.17 demonstrates the relations between concepts of the CFP and EMO ontologies.

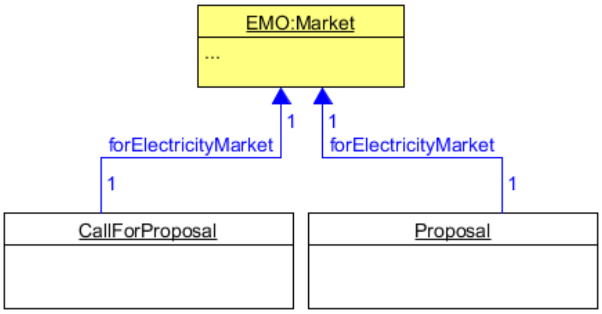


Figure 3.17 - *Call For Proposal Ontology*

As expressed before, the classes imported from the EMO are in yellow, while the object properties are represented in blue.

[12] http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl

In order to use this ontology, it should be noted that the **CallForProposal** class is used by the Market Operator agent to inform Player agents that a given market is about to begin and they should submit their proposals if they wish to participate. In response to the call for proposal (CfP), each market player interested in participating in the market sends a **Proposal** to the market operator with the respective bids and complex offers, if desired.

A CfP is sent for each market session, and each **Proposal** is an answer to the respective CfP session. For the **CallForProposal** the market operator defines its name; the **Market**'s name; the **MarketType**'s id and name; and the **Session**'s id, number, date, number of periods (numberOfPeriods) and the maximum number of fractions (**Offer**s) allowed in each **Bid** for the simulation (maxNumberOfFractions). In turn, the players answer with the **Session**'s **Periods**, including the respective **Bid**s and **Offer**s in the **Proposal**.

Similarly to the EMO, the CFP ontology also has expressivity *ALCHIQ(D)* and its DL syntax is defined in Table 3.12 (object property) and Table 3.13 (classes).

Table 3.12 - *Call For Proposal Ontology* object property DL syntax

Object Property
fromElectricityMarket ⊑ R ⊤ ⊑ ≤ 1 fromElectricityMarket

Table 3.13 - *Call For Proposal Ontology* classes DL syntax

Classes
CallForProposal ⊑ ⊤ ⊓ ∃fromElectricityMarket 1 **EMO:Market**
Proposal ⊑ ⊤ ⊓ ∃fromElectricityMarket 1 **EMO:Market**
CallForProposal ⊓ **Proposal** ⊓ **EMO:Area** ⊓ **EMO:Operator** ⊓ **EMO:Period** ⊓ **EMO:Power** ⊓ **EMO:Price** ⊓ **EMO:Offer** ⊓ **EMO:Player** ⊓ **EMO:Bid** ⊓ **EMO:Session** ⊓ **EMO:Market** ⊓ **EMO:MarketType** ⊓ **EMO:BilateralContract** = ⊥

The **CallForProposal** identifies the EM for which it is sent. This may be an abstract market such as **EMO:Market** or one of its subclasses, such as **MBL:MIBEL**, **EPX:EPEX** or **NPO:NordPool**.

In the same way, the **Proposal** includes the EM to which it responds to. **EMO:Market** or any of its subclass markets are accepted.

Both classes (**CallForProposal** and **Proposal**) make use of the same *Functional* object property to relate the classes to the respective market, *i.e.* fromElectricityMarket.

Lastly, the **CallForProposal**, the **Proposal**, the **EMO:Area**, the **EMO:Operator**, the **EMO:Period**, the **EMO:Power**, the **EMO:Price**, the **EMO:Offer**, the **EMO:Player**, the **EMO:Bid**, the **EMO:Session**, the **EMO:Market**, the **EMO:MarketType** and the **EMO:BilateralContract** classes are all Disjoint Classes.

3.3.1.8 Electricity Markets Results Ontology

The *Electricity Markets Results* (EMR)[13] ontology has been developed considering the output data each market provides for its participants. Given the similarity of the several EM results, it has been decided to gather this knowledge into a single common ontology.

The EMR ontology imports EMO and includes: seven new concepts (**BidResult**, **BlockResult**, **FlexibleResult**, **HourlyResult**, **PlayerResult**, **TradedPower** and **MarketPrice**); three new object properties (fromPlayer, fromSession and gotResult); and six data properties (blockId, flexibleId, hourlyId, periodNumber, removalJustification and removed). These concepts and properties are highlighted with red ellipses in Figure 3.18.

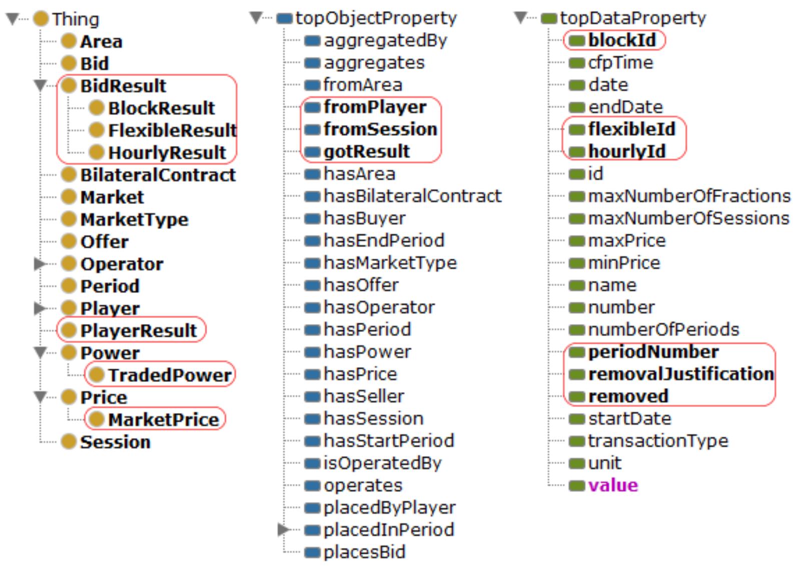


Figure 3.18 - *Electricity Markets Results Ontology* classes, object and data properties

In the left column of Figure 3.18 (in yellow) are highlighted the new classes, in the middle column (in blue) are shown the object properties, and in the right column (in green) are depicted the data properties. Analysing Figure 3.18 it is possible to observe that the **TradedPower** and **MarketPrice** concepts are subclasses of **EMO:Power** and **EMO:Price** respectively. The **BidResult** and **PlayerResult** are new concepts that have been introduced in EMR, while the **BlockResult**, **HourlyResult** and **FlexibleResult** are subclasses of **BidResult**.

Figure 3.19 illustrates the concepts and properties of EMR and its relation to the EMO ontology. Observing Figure 3.19, the objects imported from EMO are visible in yellow, while the object properties are represented in blue. The data properties are identified within each class, and the prefix “EMO:” identifies EMO’s imports.

[13] http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl

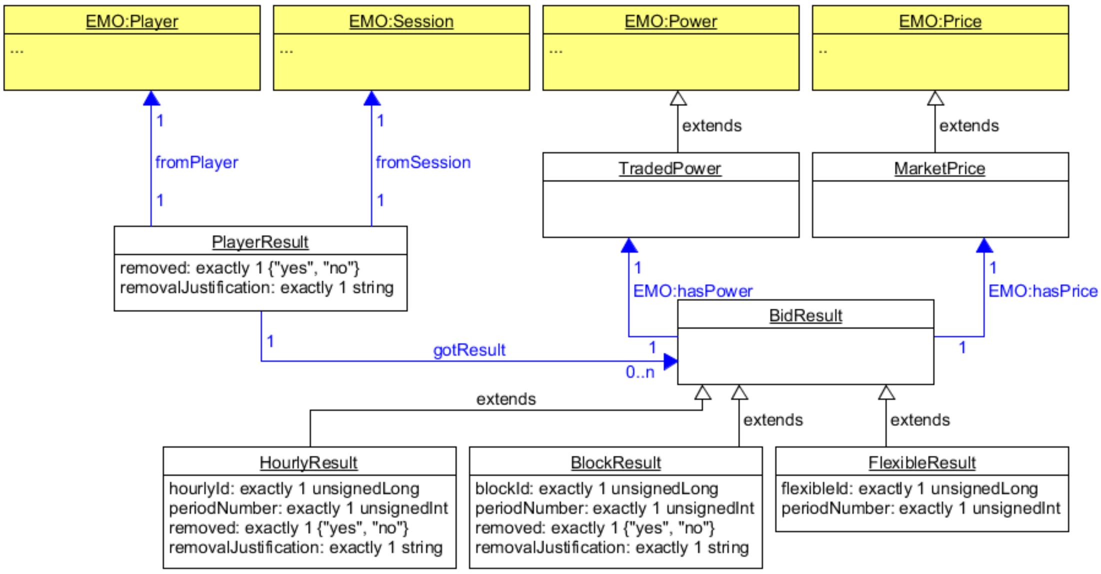


Figure 3.19 - *Electricity Markets Results Ontology*

This ontology is used by the market operators to inform the players about their results and outcomes in the market. Each **PlayerResult** corresponds to a player and identifies the several **BidResult**s of that player. For each submitted **Bid** there is a corresponding **BidResult**, and the type of bid result depends on the type of bid presented. **TradedPower** and **MarketPrice** identify the amount of power traded by the player and the market's clearing price respectively.

The EMR ontology has expressivity *ALCHIQ(D)* and its DL syntax in demonstrated in Table 3.14, Table 3.15 and Table 3.16, presenting its object properties, data properties and classes, respectively.

Table 3.14 - *Electricity Markets Results Ontology* object properties DL syntax

Object Properties	
fromPlayer $\sqsubseteq R$ $\top \sqsubseteq \leq 1$ fromPlayer	fromSession $\sqsubseteq R$ $\top \sqsubseteq \leq 1$ fromSession
gotResult $\sqsubseteq R$ $\top \sqsubseteq \leq 1$ gotResult$^-$	

Table 3.15 - *Electricity Markets Results Ontology* data properties DL syntax

Data Properties	
blockId $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ blockId	periodNumber $\sqsubseteq U$
flexibleId $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ flexibleId	removalJustification $\sqsubseteq U$
hourlyId $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ hourlyId	removed $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ removed $\top \sqsubseteq \forall$ removed.{"yes", "no"}

Table 3.16 - *Electricity Markets Results Ontology* classes DL syntax

Classes
TradedPower ⊑ **EMO:Power**
MarketPrice ⊑ **EMO:Price**
BidResult ⊑ ⊤ ⊓ ∃EMO:hasPower 1 **TradedPower** ⊓ ∃EMO:hasPrice 1 **MarketPrice**
BlockResult ⊑ **BidResult** ⊓ 1 blockId ⊓ 1 periodNumber ⊓ 1 removed ⊓ 1 removalJustification
FlexibleResult ⊑ **BidResult** ⊓ 1 flexibleId ⊓ 1 periodNumber
HourlyResult ⊑ **BidResult** ⊓ 1 hourlyId ⊓ 1 periodNumber ⊓ 1 removed ⊓ 1 removalJustification
PlayerResult ⊑ ⊤ ⊓ 1 removed ⊓ 1 removalJustification ⊓ ∃fromPlayer 1 **EMO:Player** ⊓ ∃fromSession 1 **EMO:Session** ⊓ ∃gotResult BidResult
BidResult ⊓ **PlayerResult** ⊓ **EMO:Area** ⊓ **EMO:Operator** ⊓ **EMO:Period** ⊓ **EMO:Power** ⊓ **EMO:Price** ⊓ **EMO:Offer** ⊓ **EMO:Player** ⊓ **EMO:Bid** ⊓ **EMO:Session** ⊓ **EMO:Market** ⊓ **EMO:MarketType** ⊓ **EMO:BilateralContract** = ⊥

TradedPower is subclass of **EMO:Power** inheriting its EMO:unit and EMO:value data properties. In the same way, the **MarketPrice** is a subclass of **EMO:Price**.

A **BidResult** includes a **TradedPower** and a **MarketPrice** making use of the object properties EMO:hasPower and EMO:hasPrice respectively.

As mentioned above a **BlockResult**, a **HourlyResult** and a **FlexibleResult** are subclasses of **BidResult**. The **BlockResult** and **HourlyResult** are defined by an id (blockId and hourlyId respectively), a periodNumber, a removalJustification and a removed data property with range "*yes*" and "*no*". Both blockId and removed data properties are *Functional*. The **FlexibleResult**, in turn, is only defined by a flexibleId and a removed data property.

A **PlayerResult** includes the removed and the removalJustification data properties, the respective **EMO:Player**, the considered **EMO:Session** and the corresponding **BidResult**s. The **EMO:Player** is set by the object property fromPlayer, the **EMO:Session** is set by the object property fromSession and the **BidResult**s by the object property gotResult. The three object properties are *Functional*.

Finally, the **BidResult**, the **PlayerResult**, the **EMO:Area**, the **EMO:Operator**, the **EMO:Period**, the **EMO:Power**, the **EMO:Price**, the **EMO:Offer**, the **EMO:Player**, the **EMO:Bid**, the **EMO:Session**, the **EMO:Market**, the **EMO:MarketType** and the **EMO:BilateralContract** classes are all Disjoint Classes.

3.3.1.9 AiD-EM Ontology

The *AiD-EM Ontology* (ADM)[14] has been developed aiming at providing AiD-EM's interoperability with any EM player of any agent based simulation platform. The goal is, not

[14] http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl

only to provide MASCEM's players with decision support, but also to make it available for any agent intending to participate in EM simulations.

The ADM ontology also imports EMO concepts and extends this ontology by adding new classes, object properties and data properties; and relating them with EMO's players. Figure 3.20 highlights ADM's new classes and subclasses in the left column (yellow); the object properties are demonstrated in the middle column (blue); while on the right (green) are illustrated the new included data properties.

From Figure 3.20 one can notice the large amount of objects and properties that have been included. The majority of them are related with AiD-EM's tools and its available strategies. The **Request** class, the data property totalAmountToNegotiate, and the object properties hasRequest, useTool and participateInSession are related with **EMO:Player**, while useStrategy is related with both **EMO:Player** and **EMO:Session**.

The relations between concepts of ADM are illustrated in Figure 3.21. Following the same nomenclature, the concepts imported from EMO are represented in yellow, the object properties in blue, and the data properties are included in the related classes. The "EMO:" prefix identifies the classes, object properties and data properties imported from EMO.

As it is possible to observe from Figure 3.21, AiD-EM includes a large variety of strategies to provide EM players with decision support. There are three main types of strategies from which all the remaining extend, namely **MarketStrategy**, **RLAStrategy** and **PortfolioStrategy**; where each refers to a distinct problem and can be used by more than one **Tool**. The **GameTheory** market strategy is the only one, so far, that makes use of a **ScenarioAnalysisMethod**.

When a Player requests for AiD-EM's support, it must choose, from the available strategies, the one(s) to use. ADM has been designed for communication purposes only, between AiD-EM's agents and EM players requesting for support.

ADM's expressivity is *ALCHIQ(D)*, just as EMO's, and its DL syntax is presented in Table 3.17 (object properties), Table 3.18 (data properties) and Table 3.19 (classes).

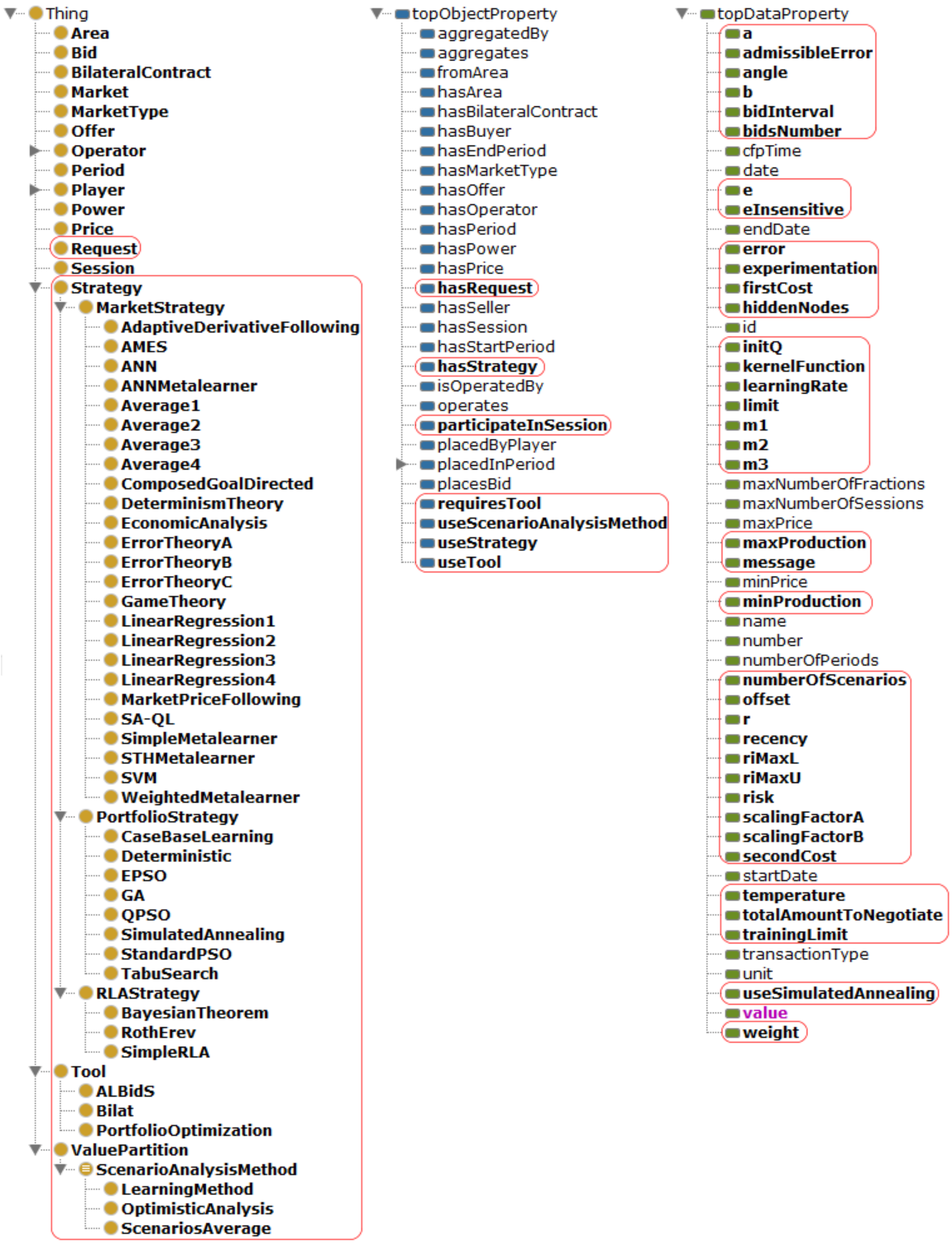


Figure 3.20 - *AiD-EM Ontology* classes, object and data properties

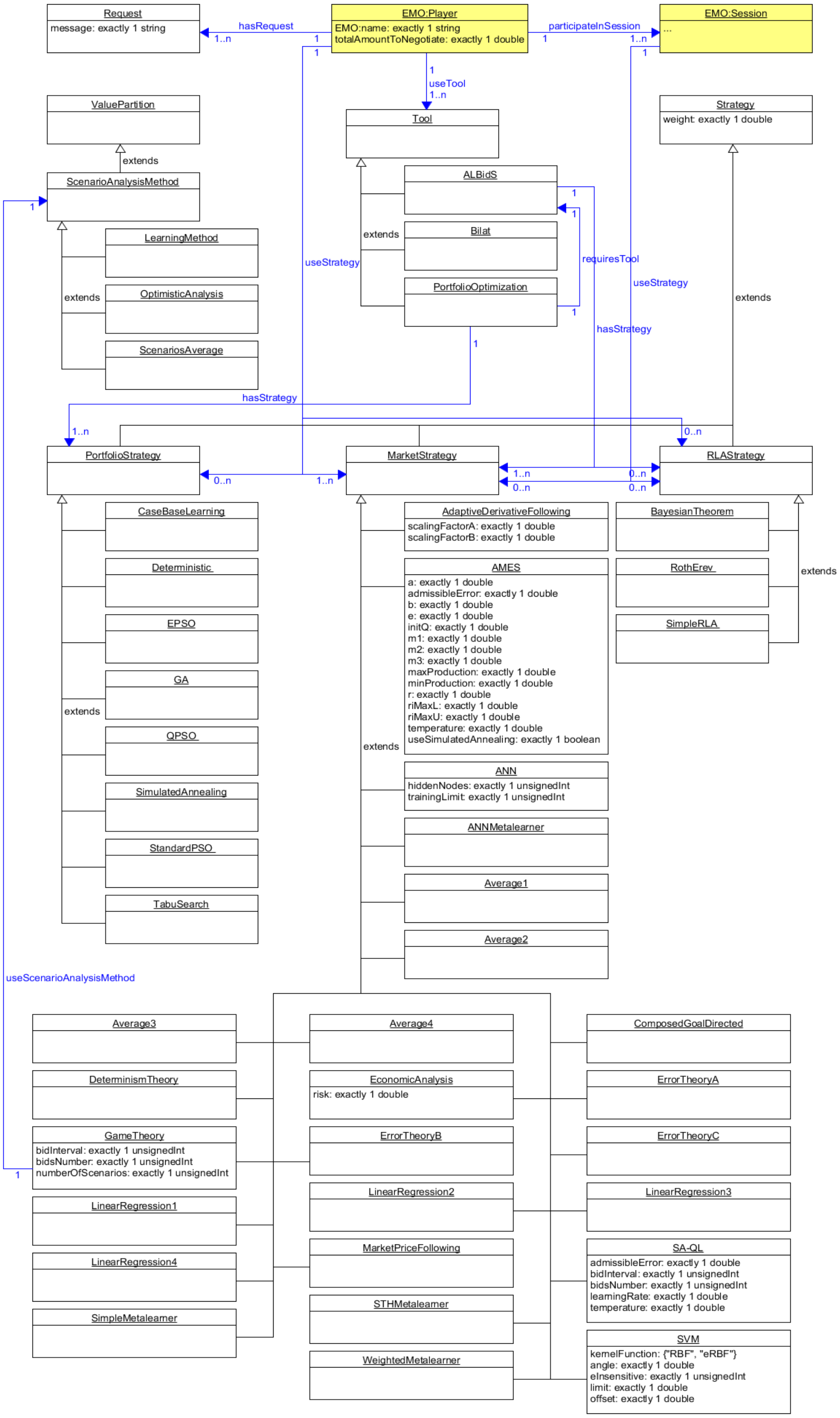


Figure 3.21 - *AiD-EM Ontology*

Table 3.17 - *AiD-EM Ontology* object properties DL syntax

Object Properties	
hasRequest $\sqsubseteq R$ $\top \sqsubseteq \leq 1$ hasRequest	useScenarioAnalysisMethod $\sqsubseteq R$ $\top \sqsubseteq \leq 1$ useScenarioAnalysisMethod
hasStrategy $\sqsubseteq R$	useStrategy $\sqsubseteq R$
participateInSession $\sqsubseteq R$	useTool $\sqsubseteq R$
requiresTool $\sqsubseteq R$	

Table 3.18 - *AiD-EM Ontology* data properties DL syntax

Data Properties	
a $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ a	maxProduction $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ maxProduction
admissibleError $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ admissibleError	message $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ message
angle $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ angle	minProduction $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ minProduction
b $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ b	numberOfScenarios $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ numberOfScenarios
bidInterval $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ bidInterval	offset $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ offset
bidsNumber $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ bidsNumber	r $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ r
e $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ e	recency $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ recency
eInsensitive $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ eInsensitive	riMaxL $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ riMaxL
error $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ error	riMaxU $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ riMaxU
experimentation $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ experimentation	risk $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ risk
firstCost $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ firstCost	scalingFactorA $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ scalingFactorA
hiddenNodes $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ scalingFactorA	scalingFactorB $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ scalingFactorB
initQ $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ initQ	secondCost $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ secondCost
kernelFunction $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ kernelFunction	temperature $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ temperature
learningRate $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ learningRate	totalAmountToNegotiate $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ totalAmountToNegotiate
limit $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ limit	trainingLimit $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ trainingLimit
m1 $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ m1	useSimulatedAnnealing $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ useSimulatedAnnealing
m2 $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ m2	weight $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ weight
m3 $\sqsubseteq U$ $\top \sqsubseteq \leq 1$ m3	

Table 3.19 - *AiD-EM Ontology* classes DL syntax

Classes
Request ⊑ ⊤ ⊓ 1 message
Strategy ⊑ ⊤ ⊓ 1 weight
ValuePartition ⊑ ⊤
ScenarioAnalysisMethod ⊑ **ValuePartition**
LearningMethod ⊑ **ScenarioAnalysisMethod**
OptimisticAnalysis ⊑ **ScenarioAnalysisMethod**
ScenariosAverage ⊑ **ScenarioAnalysisMethod**
MarketStrategy ⊑ **Strategy**
AdaptiveDerivativeFollowing ⊑ **MarketStrategy** ⊓ 1 scalingFactorA ⊓ 1 scalingFactorA
AMES ⊑ **MarketStrategy** ⊓ 1 a ⊓ 1 admissibleError ⊓ 1 b ⊓ 1 e ⊓ 1 initQ ⊓ 1 m1 ⊓ 1 m2 ⊓ 1 m3 ⊓ 1 maxProduction ⊓ 1 minProduction ⊓ 1 r ⊓ 1 riMaxL ⊓ 1 riMaxU ⊓ 1 temperature ⊓ 1 useSimulatedAnnealing
ANN ⊑ **MarketStrategy** ⊓ 1 hiddenNodes ⊓ 1 trainingLimit
ANNMetalearner ⊑ **MarketStrategy**
Average1 ⊑ **MarketStrategy**
Average2 ⊑ **MarketStrategy**
Average3 ⊑ **MarketStrategy**
Average4 ⊑ **MarketStrategy**
ComposedGoalDirect ⊑ **MarketStrategy**
DeterminismTheory ⊑ **MarketStrategy**
EconomicAnalysis ⊑ **MarketStrategy** ⊓ 1 risk
ErrorTheoryA ⊑ **MarketStrategy**
ErrorTheoryB ⊑ **MarketStrategy**
ErrorTheoryC ⊑ **MarketStrategy**
GameTheory ⊑ **MarketStrategy** ⊓ 1 bidInterval ⊓ 1 bidsNumber ⊓ 1 numberOfScenarios ⊓ ∃useScenarioAnalysisMethod 1 **ScenarioAnalysisMethod**
LinearRegression1 ⊑ **MarketStrategy**
LinearRegression2 ⊑ **MarketStrategy**
LinearRegression3 ⊑ **MarketStrategy**
LinearRegression4 ⊑ **MarketStrategy**
MarketPriceFollowing ⊑ **MarketStrategy**
SA-QL ⊑ **MarketStrategy** ⊓ 1 admissibleError ⊓ 1 bidInterval ⊓ 1 bidsNumber ⊓ 1 learningRate ⊓ 1 temperature
SimpleMetalearner ⊑ **MarketStrategy**
STHMetalearner ⊑ **MarketStrategy**
SVM ⊑ **MarketStrategy** ⊓ 1 angle ⊓ 1 eInsensitive ⊓ 1 limit ⊓ 1 offset ⊓ (kernelFunction ”RBF” ⊔ kernelFunction ”eRBF”)
WeightedMetalearner ⊑ **MarketStrategy**
PortfolioStrategy ⊑ **Strategy**
CaseBaseLearning ⊑ **PortfolioStrategy**
Deterministic ⊑ **PortfolioStrategy**
EPSO ⊑ **PortfolioStrategy**
GA ⊑ **PortfolioStrategy**
QPSO ⊑ **PortfolioStrategy**
SimulatedAnnealing ⊑ **PortfolioStrategy**
StandardPSO ⊑ **PortfolioStrategy**

TabuSearch ⊑ **PortfolioStrategy**
RLAStrategy ⊑ **Strategy**
BayesianTheorem ⊑ **RLAStrategy**
RothErev ⊑ **RLAStrategy**
SimpleRLA ⊑ **RLAStrategy**
Tool ⊑ ⊤
ALBidS ⊑ **Tool** ⊓ ∃hasStrategy **MarketStrategy** ⊓ ∃hasStrategy **RLAStrategy**
Bilat ⊑ **Tool**
PortfolioOptimization ⊑ **Tool** ⊓ ∃hasStrategy **PortfolioStrategy** ⊓ ∃requiresTool 1 **ALBidS**
Player ⊑ **EMO:Player** ⊓ 1 totalAmountToNegotiate ⊓ ∃hasRequest **Request** ⊓ ∃participateInSession **EMO:Session** ⊓ ∃useStrategy 1 **RLAStrategy** ⊓ ∃useStrategy **MarketStrategy** ⊓ ∃useStrategy **PortfolioStrategy** ⊓ ∃useTool **Tool**
Session ⊑ **EMO:Session** ⊓ ∃useStrategy 1 **RLAStrategy** ⊓ ∃useStrategy **MarketStrategy**
Request ⊓ **Strategy** ⊓ **Tool** ⊓ **ValuePartition** ⊓ **EMO:Area** ⊓ **EMO:Operator** ⊓ **EMO:Period** ⊓ **EMO:Power** ⊓ **EMO:Price** ⊓ **EMO:Offer** ⊓ **EMO:Player** ⊓ **EMO:Bid** ⊓ **EMO:Session** ⊓ **EMO:Market** ⊓ **EMO:MarketType** ⊓ **EMO:BilateralContract** = ⊥

The **Request** object includes a message, while a **Strategy** is composed by a weight data property. The **ValuePartition** class is a pattern that enables the specification and restriction of certain values that a property can be associated with. The **ScenarioAnalysisMethod** is a subclass of **ValuePartition,** being equivalent to one of its subclasses: **LearningMethod**, **OptimisticAnalysis** or **ScenariosAverage**.

The **MarketStrategy**, **PortfolioStrategy** and **RLAStrategy** are subclasses of **Strategy**. The **MarketStrategy** refers to the EM negotiation strategies; the **PortfolioStrategy** is referent to the portfolio optimization methods; and the **RLAStrategy** is related to the use of reinforcement learning algorithms (RLA) to select the most suitable strategies in each context. Besides the weight, each market strategy may include other parameters to be set by the markets' players; these parameters are identified in the ADM ontology as data properties included in the respective market strategies. On the other hand, the RLA and Portfolio strategies only allow to determine the weight.

The **Tool** concept represents an abstract tool. **ALBidS**, **Bilat** and **PortfolioOptimization** are subclasses of **Tool** since they represent AiD-EM's available tools for decision support. **ALBidS** may include one or more **MarketStrategy** and one or more **RLAStrategy**, using the object property hasStrategy. In turn, the **PortfolioOptimization** requires the use of **ALBidS**, through the use of requiresTool object property, including also a **PortfolioStrategy** by using hasStrategy too, if desired.

A **Player** is an **EMO:Player** here redefined to include: the totalAmountToNegotiate; the **Request** to be sent to AiD-EM; a **RLAStrategy**, a **MarketStrategy** and a **PortfolioStrategy**, if intended; one or more **Tool**s; and also an **EMO:Session** identifying the session in which the player will participate through the use of the participateInSession object property. **Session** is subclass of **EMO:Session** including a **RLAStrategy** and/or one or more **MarketStrategy**.

Finally, the **Request**, the **Strategy**, the **Tool**, the **ValuePartition**, the **EMO:Area**, the **EMO:Operator**, the **EMO:Period**, the **EMO:Power**, the **EMO:Price**, the **EMO:Offer**, the **EMO:Player**, the **EMO:Bid**, the **EMO:Session**, the **EMO:Market**, the **EMO:MarketType** and the **EMO:BilateralContract** classes are all Disjoint Classes.

3.3.2 Application of the proposed ontologies

Besides developing the ontologies, it is also necessary to develop Java code so that the ontologies can be interpreted and used by MASCEM's, AiD-EM's, MASGriP's and external systems' agents. For this purpose the Apache Jena[15] tool was used: "*a free and open source Java framework for building Semantic Web and Linked Data applications*".

Following the MASCEM's restructuring architecture, diverse modules have been developed, relating to each type of agent that is expected to make use of each ontology. The following subsections describe the solutions developed for each type of agent. Figure 3.22 illustrates the communications exchanged between MAS using the developed ontologies.

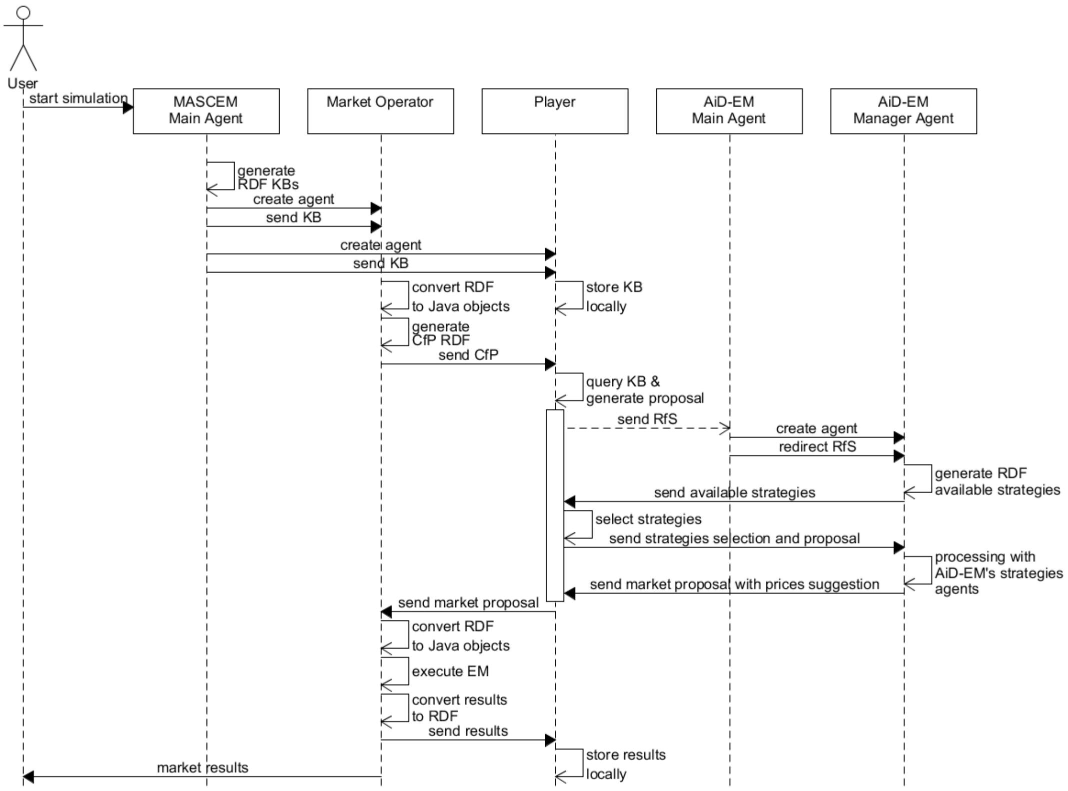


Figure 3.22 - Communications exchanged using the developed ontologies

[15] https://jena.apache.org/

3.3.2.1 MASCEM's Main Agent

The MASCEM's Main Agent is the agent responsible for the user's interaction with the agents' community. The user's input data must be converted into RDF/XML to be sent to the respective MASCEM agents, namely the players, aggregators and operators. Therefore, a module has been developed to handle this conversion before MASCEM's Main Agent creates the Market Operator, Aggregator and Player agents.

This module is basically a converter from MASCEM's input model to the respective RDF/XML list. This output list includes the RDF/XML of each MASCEM player, aggregator or operator defined in the input file.

The converter receives as input a *SimulationInputData* object. This class gathers all the data from the input file in a single instance. As mentioned before, with MASCEM's restructuring it has been decided to enable the simultaneous simulation of different scenarios, meaning that the input file may include data referring to several simulation scenarios. Each scenario is represented by a single Market Operator, which is the main responsible entity of the wholesale EM. Thus, for each Market Operator present in the *SimulationInputData* object, a list of objects is created, where each object is composed by the pair "agent name" and "RDF/XML string"; being this last the agent's knowledge base (KB).

The converter's first step is to determine the Market Operator's market in order to use the respective market's ontology, namely: MBL, EPX or NPO; otherwise the EMO is used by default. Depending on the market, the information available in the input file varies. Any player is able to participate in multiple simulations by defining the player's data in each scenario's input data.

Independently of the market, the data inputted for each agent type is rather similar. Therefore, the KB of any Market Operator must include:

- an **EMO:MarketOperator** individual identifying its EMO:name;
- an **EMO:Market** individual, identifying its EMO:name, EMO:startDate, EMO:endDate, EMO:cfpTime, the available **EMO:MarketType**(s) instances, the **EMO:Operator**(s) – including the own **EMO:MarketOperator –**, and, if defined, the **EMO:Area**(s) and **EMO:BilateralContract**(s);
- the **EMO:MarketType** individual(s) including its EMO:name, EMO:id, EMO:maxNumberOfSessions, **EMO:Session**(s) and respective **EMO:Operator**(s) instances (since each market type may include distinct operators);
- each **EMO:Session** considering its EMO:date, EMO:numberOfPeriods and EMO:maxNumberOfFractions, being also included the session's EMO:id and EMO:number;
- if determined, the **EMO:Area** including its EMO:name, maxPrice and minPrice, which can be supplemented with each market's areas constraints (*e.g.* maxNumberOfBlockOrders of EPX or NPO).

On the other hand, a Player's KB, in addition to the above mentioned **EMO:Market**, **EMO:MarketType**(s), **EMO:Session**(s) and **EMO:MarketOperator** to which its participation refers to**,** must include:

- an **EMO:Player** individual identifying its EMO:name and **EMO:Bid**(s);
- the **EMO:Bid**(s) individuals identifying the EMO:transactionType, the **EMO:Period** in which the bid is submitted, and the **EMO:Offer**(s) instance(s);
- the **EMO:Period**(s) individuals defined in the **EMO:Bid**(s) identifying the period's EMO:id and EMO:number;
- the **EMO:Offer**(s) identifying the offer's EMO:id, EMO:number and the respective **EMO:Power** and **EMO:Price**;
- the **EMO:Power**(s) and **EMO:Price**(s) identifying the corresponding EMO:unit(s) and EMO:value(s).

After iterating all simulation scenarios present in the *SimulationInputData* object, the converter outputs an object list where each element corresponds to each agent's KB. A Player agent participating in more than one simulation holds a distinct KB per scenario.

3.3.2.2 MASCEM's Market Operator

The MASCEM's Market Operator is the agent responsible for regulating the pool negotiations, validating and analysing the players' bids depending on the type of negotiation, and determining the market price, the accepted and refused bids, and the economical dispatch.

After being created and receiving its KB, the Market Operator agent converts the RDF/XML string to the corresponding Java objects, so it can be able to use the previously implemented market algorithms. When the user initializes a market simulation, the Market Operator starts by creating a Call for Proposal (CfP) RDF/XML string to be sent to the registered Players. After receiving the Player's proposals, the Market Operator agent must convert them to the respective Java objects. Once the corresponding market's session is finished, this agent converts the results of each Player into the respective RDF/XML strings to be sent afterwards.

Given these requirements, the software module developed for the Market Operator agent includes three distinct converters: (i) the first to convert the agent's KB into the respective Java objects; (ii) the second to generate the RDF/XML CfP to be sent to the market players and the respective conversion from the player's proposals to the corresponding Java objects; and (iii) the third to convert each player's result to the relative RDF/XML string.

The first converter receives as input the RDF/XML string with the Market Operator's KB. To convert it to the respective Java objects it is necessary to instantiate a Jena *OntModel* in order to be able to query the model and instantiate the Market Operator's related Java classes. The model is queried through SPARQL query language[16], a query language for RDF directed and labelled graph's data format. The query results are then converted into the correct data format to be instantiated in the Java objects.

The second converter is divided in two different parts. The first part is similar to the Main Agent's converter, since it gathers the CfP Java information and generates the corresponding

[16] http://www.w3.org/TR/sparql11-query/

RDF/XML to be sent to market's players. The CfP is relative to a market's session only, and it must include:

- a **CFP:CallForProposal** individual, identifying the **EMO:Market** it refers to;
- the **EMO:Market** identifying its EMO:name and respective **EMO:MarketType** instance;
- the **EMO:MarketType** identifying its EMO:name, EMO:id, the respective **EMO:Session**, and **EMO:MarketOperator**;
- the **EMO:MarketOperator** identifying its EMO:name;
- the **EMO:Session** defining its EMO:id, EMO:number, EMO:maxNumberOfFractions, EMO:numberOfPeriods and EMO:date.

On the other hand, the second part is related to the **CFP:Proposal**(s) received by the Market Operator(s), which must be converted into Java instances, so that the operators can execute the market simulations. For this purpose, a similar approach to the one used in the first converter has been implemented, *i.e.* using SPARQL query to obtain the data required to create the corresponding Java instances. The Player's proposals are then added to the Market Operator's model and the market is executed.

Finally, the third converter is used by the Market Operator to transform the Player's market outcomes into the respective RDF/XML string, to be later sent to each player. As explained before, the EMR ontology gathers the various results of each EM, on the other hand, each result's RDF/XML is relative to a single market session. In this way, a result's RDF/XML must include:

- an **EMR:PlayerResult** identifying the **EMO:Player**, the **EMO:Session**, and the respective **EMR:BidResult**(s);
- the **EMO:Player** identifying its EMO:name;
- the **EMO:Session** identifying its EMO:id, EMO:number and EMO:date;
- the **EMO:BidResult**(s) which depend on the electricity market in which the player has participated, but that always includes the respective id (EMR:hourlyId, EMR:blockId or EMR:flexibleId) and a **EMR:MarketPrice** and **EMR:TradedPower**;
- the **EMR:TradedPower**(s) and **EMR:MarketPrice**(s) identifying the corresponding EMO:unit(s) and EMO:value(s).

3.3.2.3 Player

The Player, in this context, refers to any market player interested in participating in MASCEM's simulations, *i.e.* a MASCEM Player, a VPP, a MASGriP SG or MG, or any other external agent willing to participate in MASCEM's EM. A Player may represent a consumer, a producer, a retailer or prosumer or an aggregator of any of these types of players. It should also be remembered that any player participating in the wholesale EM must be able to request for AiD-EM's decision support.

Taking this into consideration, the Player's module can be separated into four submodules. The first submodule is used to store the Player's KB in a given local repository. It receives as parameters the Player's KB RDF/XML string and its local repository base path. The output is the file located in the defined repository.

The second submodule concerns the Player's answer to the CfP. Once the CfP RDF/XML string is received, the Player stores it in its local repository and queries it in order to get the CfP information so it can decide whether or not to participate in the respective market. If the Player is interested in participating, then it will query its KB in order to create its market proposal and send it to the respective market operator. As input, this submodule requires the Player's name, the CfP RDF/XML string and the Player's local repository base path. The **CFP:Proposal** sent by the Player should include:

- the **EMO:Market** to which the proposal is sent, including the market's EMO:name and **EMO:MarketType**;
- the **EMO:MarketType** individual identifying its EMO:id, EMO:name, the **EMO:MarketOperator**'s instance and the respective **EMO:Session**;
- the **EMO:MarketOperator** individual identifying its EMO:name;
- the **EMO:Session** identifying its EMO:id, EMO:number, EMO:date and the respective **EMO:Period**(s);
- the **EMO:Period**(s) identifying its EMO:id and EMO:number;
- the **EMO:Player** identifying its EMO:name and placed **EMO:Bid**(s);
- the **EMO:Bid**(s) identifying its EMO:transactionType, the **EMO:Player** who places it, the **EMO:Period** where it is placed and the **EMO:Offer**(s) submitted;
- the **EMO:Offer**(s) identifying its EMO:id, EMO:number, **EMO:Price** and **EMO:Power**;
- the **EMO:Power**(s) and **EMO:Price**(s) identifying the corresponding EMO:unit(s) and EMO:value(s).

The third submodule is similar to the first, but its difference is that it stores the market results received after the EM's execution in the player's local repository.

The fourth and final submodule is related with AiD-EM's request for support. This submodule may also be divided in three separate parts. The first part creates the player's request for support message sent to the AiD-EM's Main Agent, which includes: (i) the **EMO:Player** requesting for support, identifying its EMO:name; and (ii) the **ADM:Request** including a ADM:message requesting for support. The second part deals with the strategies' selection made by the player after the AiD-EM's Manager Agent, assigned to this Player, sends the available strategies for decision support. In addition to the strategies, the Player must also include in this RDF/XML its proposal for the respective market's session. Hence, besides the information previously described in the second submodule about the player's proposal, this RDF/XML must also include: (i) in the **EMO:Player,** the ADM:totalAmountToNegotiate, the **ADM:Tool**(s) and **ADM:Strategy**(ies) selected by the player; (ii) the **ADM:Tool**(s) individuals; and (iii) for the selected **ADM:Strategy**(ies), their respective parameters. The final and third part of this submodule receives the proposal sent by the AiD-EM's Manager Agent and redirects it to the MASCEM's Market Operator as the player's proposal for the given market's session.

3.3.2.4 AiD-EM's Main Agent

The AiD-EM's Main Agent, with a similar role to MASCEM's Main agent, is the agent responsible for the users' and agents' interaction with AiD-EM's agents society. The users' input in AiD-EM determines the available tools and strategies for the decision support. On the other hand, an agent that desires to request for AiD-EM's support must first request it to AiD-EM's Main Agent. In order to meet these purposes, a module has been developed, so that this agent can be able to receive the players' requests, interpret them and later redirect the request to a dedicated Manager Agent.

This module has the task of interpreting the requests for support (RfS) sent by market players, in order to delegate an individual Manager Agent for each player. It basically queries the RfS RDF/XML to read the player's message. After reading its message, the Manager Agent registers the player in AiD-EM and generates a Manager Agent to support this player in the market.

3.3.2.5 AiD-EM's Manager Agent

The AiD-EM's Manager Agent is the agent responsible for helping the player during the decision support process. This agent is created by AiD-EM's Main Agent aiming at supporting the player until the market session ends.

The module developed for this agent may also be separated in two submodules: (i) the first generates a selection of the available tools and strategies for the player to use; (ii) while the last creates a market proposal with prices suggestions achieved by the decision support tools.

The first submodule gets as input the player's name and outputs the available tools and strategies for decision support in AiD-EM. The RDF/XML generated includes: (i) the available **ADM:Tool**(s) identifying the respective **ADM:Strategy**(ies); and (ii) the **ADM:Strategy**(ies) of the available **ADM:Tool**(s).

The second and final submodule generates a **CFP:Proposal** similar to the one sent by the player (already described in subsection 3.3.2.3), but considering the prices suggested by the decision support tools.

3.4 Final Remarks

This chapter has presented MASCEM's restructuring and the developed ontologies for semantic interoperability between heterogeneous MAS in the scope of the wholesale EM.

MASCEM's restructuring has become fundamental, considering the constant evolution of EM models. MASCEM's complexity for updating old models or for developing new ones, together with the limitations of the old architecture and development platform, were the main drivers that led to this restructuring process. The main goal of this restructuring was to optimize the simulator's performance while providing the means to cope with the evolving, complex and dynamic EM reality.

With this renewed and enhanced agent based simulator, models may be easily enlarged allowing to accomplish the future evolution of markets. This restructuring potentiates the inclusion of new or updated models, providing the means for the interoperability with other MAS, reflecting one of the main advantages of multi-agent societies.

In order to disseminate the development of interoperable MAS within power engineering, interconnection issues must be addressed. To take full advantage of these systems, there is a growing need for knowledge exchange with the aim at providing full interoperability between different systems. With the objective of overcoming these issues, an *Electricity Markets Ontology* (EMO) is proposed, gathering the EM main concepts, enabling the interoperability of independently developed multi-agent based simulation platforms.

Besides EMO, specific ontologies have been developed, which are dedicated to different market operators, in specific MIBEL, EPEX and Nord Pool. Additionally, particular ontologies conceived to deal with the different communication processes (between market players and market operators, and between players and the AiD-EM system) have also been developed. EMO can be seen here has a "main" ontology from which the remaining are extended by importing its concepts and relations. Their domain and scope are identified, discriminating each ontology independently. Using this ontological structure, the different types of agents are able to communicate with each other, understanding a common language, while providing the means for any agent from external systems to do the same, simply by importing the developed ontologies.

The application and use of the developed ontologies by the respective software agents is also explained and described. Given that MASCEM, AiD-EM and MASGriP are being developed using the JADE framework, Java code has been implemented to facilitate the use of the ontologies.

The applicability and advantage of using the proposed ontologies in the frame of the restructured MASCEM simulator is discussed in chapter 4. The considered case studies demonstrate the applicability of the ontologies in simulations characterized by interactions among GECAD's power engineering MAS (MASCEM, MASGriP and AiD-EM). These simulations also show the advantages of MASCEM's restructuring, which has optimized the overall system's performance.

4 Case Studies

4.1 Introduction

This chapter presents three case studies which aim to demonstrate MASCEM's operation after the restructuring process and the use of the developed ontologies for the interoperability with other MAS.

Although each ontology has been tested during its development, it is essential to prove its utility in the interoperability between the various MAS. The presented case studies consider the most relevant features to be exhibited.

The first case study demonstrates the use of the ontologies to support players' participation in three different European markets, where each player takes advantage of the public ontologies to bid in the markets as if they were local markets.

Regarding the second case study, the focus is on the interoperability between MASCEM and AiD-EM [Pinto *et al.*, 2015a]. In this case, one of MASCEM's players makes use of the developed ontologies to request the decision support provided by AiD-EM multi-agent platform.

Finally, the interoperability between MASCEM and MASGriP [Oliveira *et al.*, 2012], and between MASGriP and AiD-EM is illustrated in the third case study. The case study is divided into two scenarios: a) the first scenario exposes the participation of a MASGriP player in a MASCEM's electricity market simulation; and b) the second scenario explores the use of AiD-EM's decision support by the same player, in order to try to maximize the MASGriP player's profits in market negotiations.

4.2 Case Study 1 – European electricity markets

This case study is based on four scenarios, created using RealScen [Teixeira *et al.*, 2014], a scenarios generation tool developed in GECAD, using real data extracted from several European market operators, through an extraction tool [Pereira *et al.*, 2014]. These scenarios have been created with the intention of representing the European reality through a summarized group of players, representing buyer and seller entities of each area of each regional market (*e.g.* in the Iberian market, each area represents a country: Portugal and Spain; while in other regional markets each area represents a different zone, such as several parts of different countries, *e.g.* Nord Pool; or several parts of the same country, *e.g.* GME).

The simulation scenarios include two agents for each area (a seller and a buyer), practicing the average prices and negotiating the total amount of power that have been transacted in each of these areas in the reality, for each of the considered simulation days. Forty one areas are considered, *i.e.* 41 buyers and 41 sellers, resulting in a total of 82 players for these simulation scenarios.

The four selected scenarios consider two days during the summer, and other two during the winter; and for each, one business day (Wednesday) and one weekend day (Sunday). The selected days were: 25th July, 2012 (Wednesday); 29th July, 2012 (Sunday); 16th January, 2013 (Wednesday); and 20th January, 2013 (Sunday). These dates have been selected because they represent regular days, concerning the transacted power volume and market price in each season.

The players, representing the entire European Continent, negotiate in a common market environment, simulating the PAN-European Electricity Market [EMCC, 2015]. Three market mechanisms are considered, all regarding day-ahead negotiations: the EPEX SPOT [EPEX, 2015]; the MIBEL spot market [OMIE, 2015]; and Elspot market from Nord Pool [Nord Pool, 2015]. All players negotiate using each of these three market mechanisms, for each of the four days. Players' behaviour is assumed as if they are participating in their origin market, *e.g.* players from markets where complex conditions are permitted use the particularities of each of the other market mechanisms to transpose the condition as best as possible (a good example is the *Indivisibility* complex condition from MIBEL [OMIE, 2015], [Santos *et al.*, 2011], which can be easily replaced with a Elspot or EPEX SPOT block offer [EPEX, 2015], [Nord Pool, 2015], and vice versa).

As the simulation starts, MASCEM's Main Agent reads the input excel file to generate the players involved in the simulation and their respective knowledge base (KB) files. After being created, each agent receives a message from the MASCEM's Main Agent with their KB represented in RDF. Figure 4.1 presents the RDF message received by the Nord Pool Market Operator and Figure 4.2 shows a snippet of the RDF sent to agent Seller 22, both for the day of 25th July, 2012. The complete RDF messages are available online[17].

Analysing Figure 4.1 it can be observed the definition of an electricity market named "*NORDPOOL*" (from line 14 to line 22) which has an operator named "*NORDPOOL 2012 07 25*" (between lines 10 and 13) and a market type named "*SPOT*" (from line 35 to 42), also operated by the "*NORDPOOL*" market operator. In turn, the market type "*SPOT*" (between lines 35 to 42) has only one session (the "*maxNumberOfSessions*" is 1) of the type "*ElspotSession*" (defined from line 27 to 34), considering 24 hourly periods (the "*numberOfPeriods*" is 24).

[17] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/1/#rdf-2

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
4   xmlns:nordpool="http://www.mascem.gecad.isep.ipp.pt/ontologies/nordpool.owl#"
5   xmlns:owl="http://www.w3.org/2002/07/owl#"
6   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
7   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
8   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
9   xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
10   <rdf:Description rdf:about="nordpool.owl#iMO-NORDPOOL_2012_07_25">
11     <emo:name>NORDPOOL 2012 07 25</emo:name>
12     <rdf:type rdf:resource="electricity-markets.owl#MarketOperator"/>
13   </rdf:Description>
14   <rdf:Description rdf:about="nordpool.owl#iM-NORDPOOL">
15     <emo:hasMarketType rdf:resource="nordpool.owl#iMT-SPOT"/>
16     <emo:cfpTime rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">60000
       </emo:cfpTime>
17     <emo:endDate rdf:datatype="http://www.w3.org/2001/XMLSchema#date">2012-07-25
       </emo:endDate>
18     <emo:startDate rdf:datatype="http://www.w3.org/2001/XMLSchema#date">2012-07-25
       </emo:startDate>
19     <emo:name>NORDPOOL</emo:name>
20     <emo:hasOperator rdf:resource="nordpool.owl#iMO-NORDPOOL_2012_07_25"/>
21     <rdf:type rdf:resource="nordpool.owl#NordPool"/>
22   </rdf:Description>
23   <rdf:Description rdf:about="nordpool.owl#">
24     <owl:imports rdf:resource="nordpool.owl#"/>
25     <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#Ontology"/>
26   </rdf:Description>
27   <rdf:Description rdf:about="nordpool.owl#iElspotSession2012-07-25-0">
28     <emo:maxNumberOfFractions rdf:datatype="
       http://www.w3.org/2001/XMLSchema#unsignedInt">1</emo:maxNumberOfFractions>
29     <emo:numberOfPeriods rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">
       24</emo:numberOfPeriods>
30     <emo:date rdf:datatype="http://www.w3.org/2001/XMLSchema#date">2012-07-25
       </emo:date>
31     <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">0
       </emo:number>
32     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       6768671844112679792</emo:id>
33     <rdf:type rdf:resource="nordpool.owl#ElspotSession"/>
34   </rdf:Description>
35   <rdf:Description rdf:about="nordpool.owl#iMT-SPOT">
36     <emo:hasSession rdf:resource="nordpool.owl#iElspotSession2012-07-25-0"/>
37     <emo:isOperatedBy rdf:resource="nordpool.owl#iMO-NORDPOOL_2012_07_25"/>
38     <emo:maxNumberOfSessions rdf:datatype="
       http://www.w3.org/2001/XMLSchema#unsignedInt">1</emo:maxNumberOfSessions>
39     <emo:name>SPOT</emo:name>
40     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       5028184771267710553</emo:id>
41     <rdf:type rdf:resource="nordpool.owl#Elspot"/>
42   </rdf:Description>
43 </rdf:RDF>
```

Figure 4.1 - Nord Pool Market Operator's knowledge base RDF

From Figure 4.2, it is readily apparent the price offered for period 22 (from line 14 to line 18) and power available for period 17 of negotiation (between lines 19 and line 23). The market operator's name definition is also visible (lines 10 to 13), with whom the player will communicate.

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:nordpool="http://www.mascem.gecad.isep.ipp.pt/ontologies/nordpool.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="nordpool.owl#iMO-NORDPOOL_2012_07_25">
    <emo:name>NORDPOOL 2012 07 25</emo:name>
    <rdf:type rdf:resource="electricity-markets.owl#MarketOperator"/>
  </rdf:Description>
  <rdf:Description rdf:about="nordpool.owl#iPrice1-P22-ElspotSession2012-07-25-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">9.86
    </emo:value>
    <emo:unit>EUR</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Price"/>
  </rdf:Description>
  <rdf:Description rdf:about="nordpool.owl#iPower1-P17-ElspotSession2012-07-25-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">2156.7
    </emo:value>
    <emo:unit>MW</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Power"/>
  </rdf:Description>
  <rdf:Description rdf:about="nordpool.owl#iPeriod18-ElspotSession2012-07-25-0">
    <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">18
    </emo:number>
    <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
    6800659025727251849</emo:id>
    <rdf:type rdf:resource="electricity-markets.owl#Period"/>
  </rdf:Description>
  <rdf:Description rdf:about="nordpool.owl#iHourlyOrder14-ElspotSession2012-07-25-0">
    <emo:hasOffer rdf:resource="nordpool.owl#iOffer1-P14-ElspotSession2012-07-25-0"/>
    <emo:transactionType>sell</emo:transactionType>
    <emo:placedByPlayer rdf:resource="nordpool.owl#iSeller_22"/>
    <emo:placedInSinglePeriod rdf:resource=
     "nordpool.owl#iPeriod14-ElspotSession2012-07-25-0"/>
    <rdf:type rdf:resource="nordpool.owl#HourlyOrder"/>
  </rdf:Description>
  <rdf:Description rdf:about="nordpool.owl#iPower1-ElspotSession2012-07-25-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">2000.0
    </emo:value>
    <emo:unit>MW</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Power"/>
  </rdf:Description>
  <rdf:Description rdf:about="nordpool.owl#iHourlyOrder20-ElspotSession2012-07-25-0">
    <emo:hasOffer rdf:resource="nordpool.owl#iOffer1-P20-ElspotSession2012-07-25-0"/>
    <emo:transactionType>sell</emo:transactionType>
    <emo:placedByPlayer rdf:resource="nordpool.owl#iSeller_22"/>
    <emo:placedInSinglePeriod rdf:resource=
    "nordpool.owl#iPeriod20-ElspotSession2012-07-25-0"/>
    <rdf:type rdf:resource="nordpool.owl#HourlyOrder"/>
  </rdf:Description>
```

Figure 4.2 - Seller 22’s RDF knowledge base snippet for Nord Pool market

The simulation begins with the market operators sending the call for proposals to all the registered players. Figure 4.3 shows the call for proposal (CfP) sent by the Nord Pool market operator present in this simulation, for the day 25th July, 2012.

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
4   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
5   xmlns:nordpool="http://www.mascem.gecad.isep.ipp.pt/ontologies/nordpool.owl#"
6   xmlns:owl="http://www.w3.org/2002/07/owl#"
7   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
8   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
9   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
10  xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
11   <rdf:Description rdf:about="nordpool.owl#iM-NORDPOOL">
12     <emo:hasMarketType rdf:resource="nordpool.owl#iMT-SPOT"/>
13     <emo:name>NORDPOOL</emo:name>
14     <rdf:type rdf:resource="nordpool.owl#NordPool"/>
15   </rdf:Description>
16   <rdf:Description rdf:about="call-for-proposal.owl#">
17     <owl:imports rdf:resource="nordpool.owl#"/>
18     <owl:imports rdf:resource="call-for-proposal.owl#"/>
19     <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#Ontology"/>
20   </rdf:Description>
21   <rdf:Description rdf:about="electricity-markets.owl#iMO-NORDPOOL_2012_07_25">
22     <emo:name>NORDPOOL 2012 07 25</emo:name>
23     <rdf:type rdf:resource="electricity-markets.owl#MarketOperator"/>
24   </rdf:Description>
25   <rdf:Description rdf:about="nordpool.owl#iElspotSession2012-07-25-0">
26     <rdf:type rdf:resource="nordpool.owl#ElspotSession"/>
27     <emo:maxNumberOfFractions rdf:datatype="
       http://www.w3.org/2001/XMLSchema#unsignedInt">1</emo:maxNumberOfFractions>
28     <emo:numberOfPeriods rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt"
       >24</emo:numberOfPeriods>
29     <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">0
       </emo:number>
30     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       6768671844112679792</emo:id>
31     <emo:date rdf:datatype="http://www.w3.org/2001/XMLSchema#date">2012-07-25
       </emo:date>
32   </rdf:Description>
33   <rdf:Description rdf:about="nordpool.owl#iMT-SPOT">
34     <rdf:type rdf:resource="nordpool.owl#Elspot"/>
35     <emo:isOperatedBy rdf:resource="electricity-markets.owl#iMO-NORDPOOL_2012_07_25"
       />
36     <emo:hasSession rdf:resource="nordpool.owl#iElspotSession2012-07-25-0"/>
37     <emo:name>SPOT</emo:name>
38     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       5028184771267710553</emo:id>
39   </rdf:Description>
40   <rdf:Description rdf:about="call-for-proposal.owl#iCFP-ElspotSession2012-07-25-0">
41     <cfp:forElectricityMarket rdf:resource="nordpool.owl#iM-NORDPOOL"/>
42     <rdf:type rdf:resource="call-for-proposal.owl#CallForProposal"/>
43   </rdf:Description>
44 </rdf:RDF>
```


Figure 4.3 - Nord Pool Market Operator's CfP RDF

Analysing the CfP above, it is possible to check from line 40 to line 43 the definition of a *CallForProposal* for the electricity market named "*NORDPOOL*" (defined from line 11 to 15), with market type "*SPOT*" (between lines 33 and 39) and session "*ElspotSession*" (from line 25 to 32). After receiving the CfP, each player queries its KB in order to send its proposal to the respective market operator. Figure 4.4, Figure 4.5 and Figure 4.6 present examples of the market proposals sent by Seller 22 to each of the market operators, for the same day. The complete versions are available online[18], where the prices and amount of power to trade in each market is more easily perceptible.


```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:epex="http://www.mascem.gecad.isep.ipp.pt/ontologies/epex.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="epex.owl#iOffer1-P3-DayAheadSession2012-07-25-0">
    <emo:hasPrice rdf:resource="epex.owl#iPrice1-P3-DayAheadSession2012-07-25-0"/>
    <emo:hasPower rdf:resource="epex.owl#iPower1-P3-DayAheadSession2012-07-25-0"/>
    <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">1
    </emo:number>
    <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
    8611796767900337750</emo:id>
    <rdf:type rdf:resource="electricity-markets.owl#Offer"/>
  </rdf:Description>
  <rdf:Description rdf:about="epex.owl#iPrice1-P12-DayAheadSession2012-07-25-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">8.55
    </emo:value>
    <emo:unit>EUR</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Price"/>
  </rdf:Description>
```


Figure 4.4 - Proposal presented by Seller 22 to EPEX


```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="mibel.owl#iPeriod13-DayAheadSession2012-07-25-0">
    <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">13
    </emo:number>
    <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
    325085679901770892</emo:id>
    <rdf:type rdf:resource="electricity-markets.owl#Period"/>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iPower1-P19-DayAheadSession2012-07-25-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">2190.1
    </emo:value>
    <emo:unit>MW</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Power"/>
  </rdf:Description>
```


Figure 4.5 - Proposal presented by Seller 22 to MIBEL

[18] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/1/#rdf-4
http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/1/#rdf-5
http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/1/#rdf-6

```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:nordpool="http://www.mascem.gecad.isep.ipp.pt/ontologies/nordpool.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="nordpool.owl#iMO-NORDPOOL_2012_07_25">
    <emo:name>NORDPOOL 2012 07 25</emo:name>
    <rdf:type rdf:resource="electricity-markets.owl#MarketOperator"/>
  </rdf:Description>
  <rdf:Description rdf:about="nordpool.owl#iPrice1-P22-ElspotSession2012-07-25-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">9.86
    </emo:value>
    <emo:unit>EUR</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Price"/>
  </rdf:Description>
```


Figure 4.6 - Proposal presented by Seller 22 to Nord Pool

After receiving the proposals and validating all incoming offers, each market operator analyses the bids, and generates the RDF results to be sent to the participating players. The RDF results achieved by Seller 22 in each of the markets for the day 25th July, 2012 are illustrated in Figure 4.7, Figure 4.8 and Figure 4.9. The full version of these RDF can be found online[19], where the results may be observed with better insight.


```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:emr="
 http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl#"
 xmlns:epex="http://www.mascem.gecad.isep.ipp.pt/ontologies/epex.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-24">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-HourlyResult-24"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-HourlyResult-24"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">24
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
  </rdf:Description>
  <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-12">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-HourlyResult-12"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-HourlyResult-12"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">12
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
  </rdf:Description>
```


Figure 4.7 - Results achieved by Seller 22 on EPEX

[19] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/1/#rdf-7
http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/1/#rdf-8
http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/1/#rdf-9

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:emr="
 http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl#"
 xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-24">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-HourlyResult-24"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-HourlyResult-24"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">24
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
  </rdf:Description>
  <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-12">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-HourlyResult-12"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-HourlyResult-12"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">12
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
  </rdf:Description>
```

Figure 4.8 - Results achieved by Seller 22 on MIBEL

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:emr="
 http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl#"
 xmlns:nordpool="http://www.mascem.gecad.isep.ipp.pt/ontologies/nordpool.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="electricity-markets-results.owl#iFlexibleResult-2">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-FlexibleResult-2"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-FlexibleResult-2"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">2
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#FlexibleResult"/>
  </rdf:Description>
  <rdf:Description rdf:about=
  "electricity-markets-results.owl#iTradedPower-FlexibleResult-11">
    <emo:unit>MW</emo:unit>
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
    <rdf:type rdf:resource="electricity-markets-results.owl#TradedPower"/>
  </rdf:Description>
```

Figure 4.9 - Results achieved by Seller 22 on Nord Pool

Figure 4.7 and Figure 4.8 present hourly results for the periods 12 and 24 (between lines 11 and 22), while Figure 4.9 shows the flexible result achieved by Seller 22 on period 2 (from line 11 to 16).

Figure 4.10 presents the market results for each of the four considered days, using each of the three market types' mechanisms.

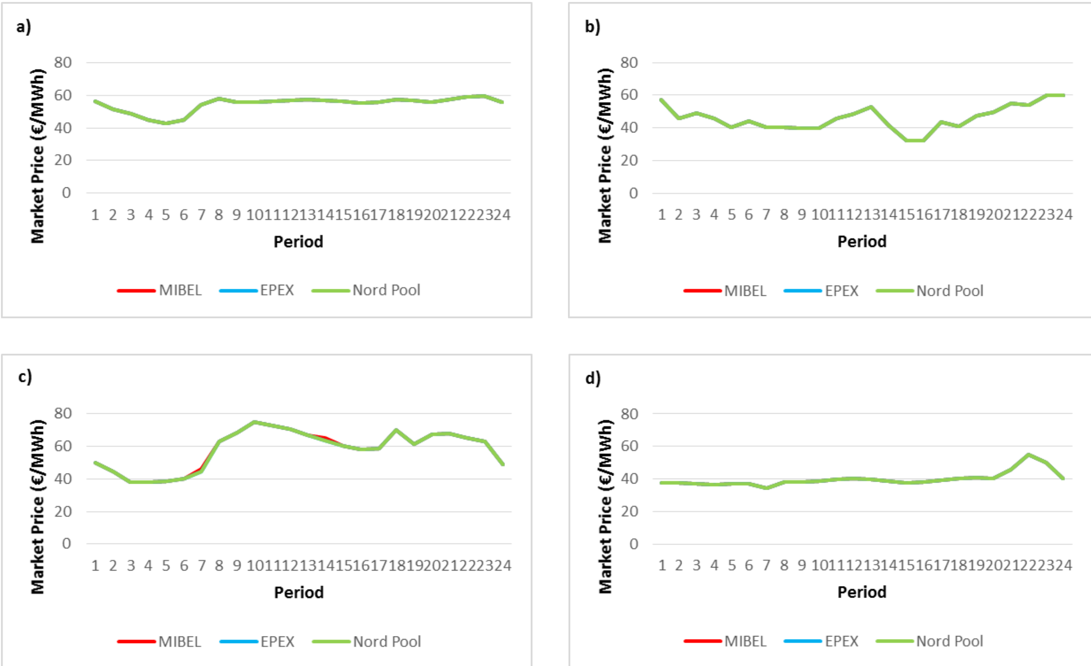


Figure 4.10 - Electricity market prices for the conjunct participation of all European countries in: a) 25th July, 2012; b) 29th July, 2012; c) 16th January, 2013; d) 20th January, 2013.

From Figure 4.10 it visible that the market prices are almost the same, every day, when using the three market mechanisms. In the case of 16th January, 2013, show in Figure 4.10 c) the market prices in MIBEL in periods 7 and 14 differ slightly from the other.

These small differences are due to the fact that, in spite of the three market mechanisms being based on a symmetric auction (*i.e.* the basis of the markets is identical), all markets present particularities that distinguishes them. The possibility of presenting complex conditions, block offers and flexible offers, gives the participant players the chance to adapt their behaviour to the specificities of each market. This means that the way players act in each market has a direct influence on the outcomes of the market, therefore the use of simulation tools, which allow them to test new approaches in order to learn how to act in a new environment, is a critical issue.

Regarding the seasonal differences, when comparing the four simulated days, a small decrease in the prices is verified from summer to winter. This decrease is also visible in all markets during the weekend days when compared to the business days of the same season.

Considering the results of each player in the three different EM, it is possible to determine the social welfare (SW) to evaluate the global players' benefits in each one. The SW is calculated as in (1), following the principles presented in [Wu *et al.*, 2008].

$$SW = \sum_{t=1}^{T} \left[\begin{array}{l} \sum_{Seller=1}^{N_{Seller}} \sum_{Bid=1}^{N_{Bid}} P_{(Seller,Bid,t)} \times \left(MP_{(t)} - BP_{(Seller,Bid,t)}\right) \times BA_{(Seller,Bid,t)} + \\ \sum_{Buyer=1}^{N_{Buyer}} \sum_{Bid=1}^{N_{Bid}} P_{(Buyer,Bid,t)} \times \left(BP_{(Buyer,Bid,t)} - MP_{(t)}\right) \times BA_{(Buyer,Bid,t)} \end{array} \right] \quad (1)$$

where $P_{(Player,Bid,t)}$ and $BP_{(Player,Bid,t)}$ are the power and price offered by the player (Seller or Buyer) in a specific bid for period t, respectively. $MP_{(t)}$ is the market clearing price in period t and $BA_{(Player,Bid,t)}$ is a binary variable which indicate if the bid for period t was accepted. The results are presented in Figure 4.11.

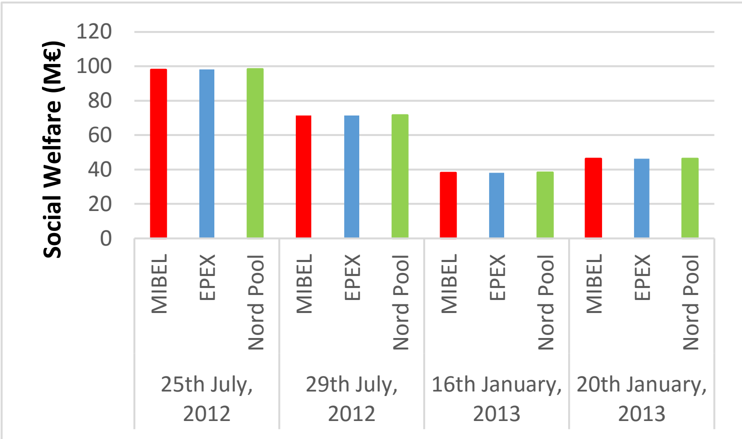


Figure 4.11 - Social welfare

As it is possible to see in Figure 4.11, the SW is similar in the three markets. In all days, the Nord Pool presents a slightly higher SW, with an average difference of 0.3%. The differences of SW are marginal for the different markets in the same day because all the markets use a symmetric clearing mechanism. Additionally, the values represent the sum of the SW of all periods, absorbing the differences that may exist in individual periods. In contrast, the SW changes significantly in different days due to the differences in the demand requirements and mainly in the resources (production) availability.

In order to illustrate the impact of using different types of offers, available in the different markets, the outcomes of one particular seller (Seller 22) are analysed, when participating in the three different market mechanisms, for the day of 25th July, 2012. This player uses the proposed ontology to participate in the different market mechanisms while maintaining, as possible, its strategic approach for market negotiations.

Figure 4.12 presents the results of Seller 22 during the daily market session, using the MIBEL market mechanism. This player uses the *Indivisibility* complex condition, to ensure that the whole production amount is sold.

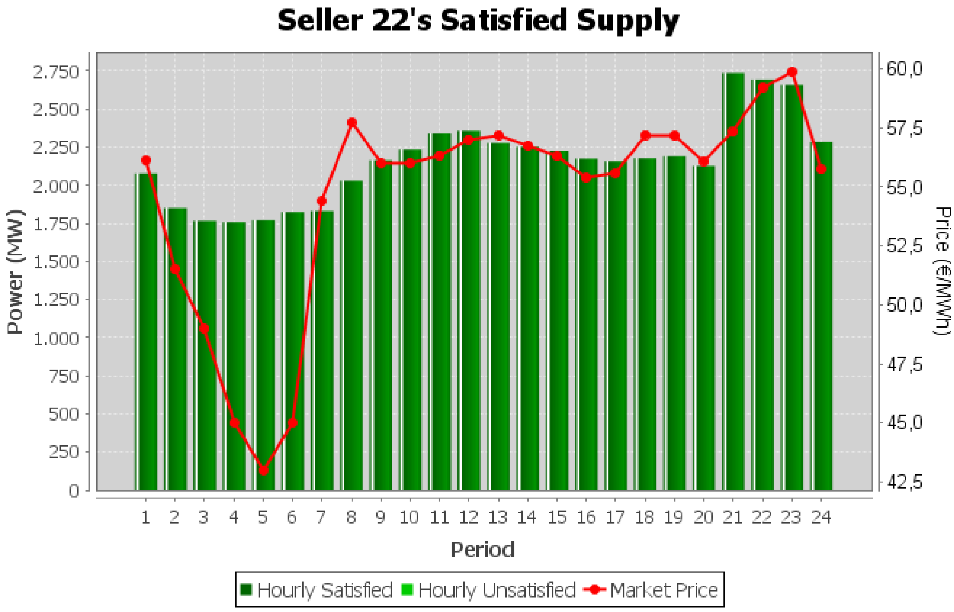


Figure 4.12 - Market results of Seller 22 when participating in the MIBEL market mechanism, with the *Indivisibility* complex condition.

Given that Seller 22 needs to sell all of its available energy, the bid price that this player submitted was very low when compared to the average, expected, market price. As a result, all of the energy available was indeed sold in the market, as it is possible to observe in Figure 4.12.

Figure 4.13 presents the market results for Seller 22, when participating in the EPEX spot market, using block offers. This type of offer can be seen as a group of single hourly offers, where each order can have a different amount of energy, but all have the same price. The orders included in the block must belong to three or more consecutive hours.

These orders have a *fill-or-kill* condition, which means that all of the orders must be accepted in the market for the block to be negotiated. If only block offers are used, it would be very similar to the use of the *Indivisibility* condition of MIBEL. The use of the agents' ontologies allows players to be aware of this. However, since the main objective of this player is to sell as much power as possible, Seller 22 offers the majority of its available power at low prices, but using the block offers trying to optimize the price on a smaller amount of power, assuming that risk.

The block order submitted by Seller 22 is composed of 24 individual orders, one for each of the 24 hourly periods of the market session. The same energy volume was defined for all of the orders (200 MWh) and the price set for the block is 44 €/MWh.

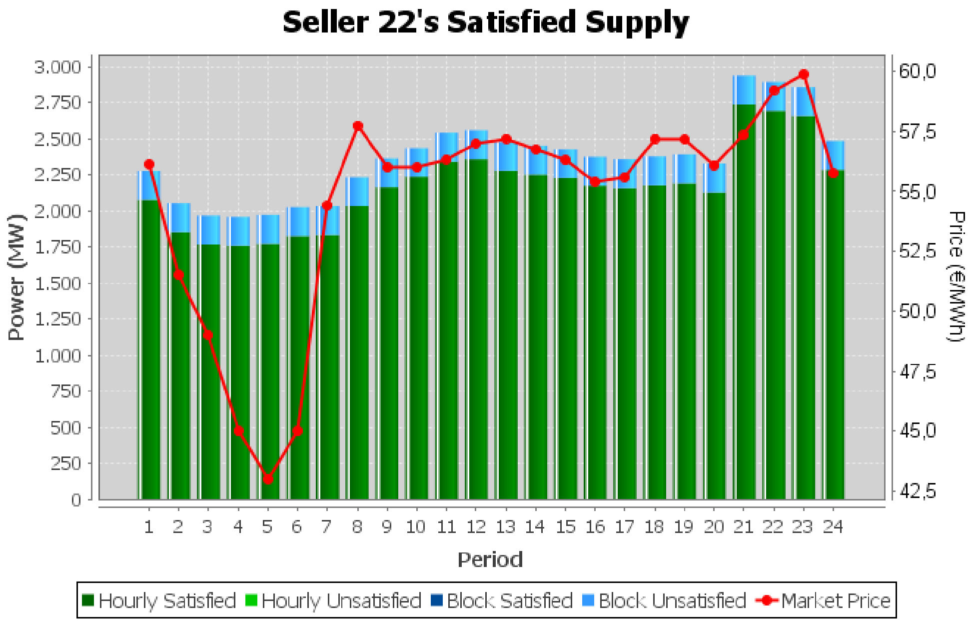


Figure 4.13 - Market results of Seller 22 when participating in the EPEX market mechanism, using block orders.

It is possible to observe in Figure 4.13, that the block was not accepted, despite its price being lower than the market price on 23 of the 24 hourly periods. The market price of the 5th period was set at 42 €/MWh (below the block offer price), which caused the entire block being refused in the market, according with the *fill-or-kill* condition.

Finally, Figure 4.14 presents the results of Seller 22 when participating in the European Market scenario, using the Nord Pool – Elspot mechanism. In this market mechanism, Seller 22 uses three flexible hourly orders. These flexible hourly orders (available only to seller agents), allow the players to specify a fixed price and volume. The hour is not specified. The order will be accepted in the hour that optimizes the overall socioeconomic welfare of the market. A maximum of five flexible hourly orders is available per agent during a market session. In this scenario three orders were submitted with the volume of 2000 MWh each, all at the same price of 40 €/MWh.

It is possible to observe from the chart of Figure 4.14 that during the first twenty one periods (hours) none of the orders was accepted although bid price being below the established market price. The light yellow bars indicate a total of 6000 MWh of unsold energy during these periods (referring to the total of the three flexible offers, of 2000 MWh each). The flexible hourly orders were accepted in the 22nd hourly period. In this period the total amount of energy of the order was sold.

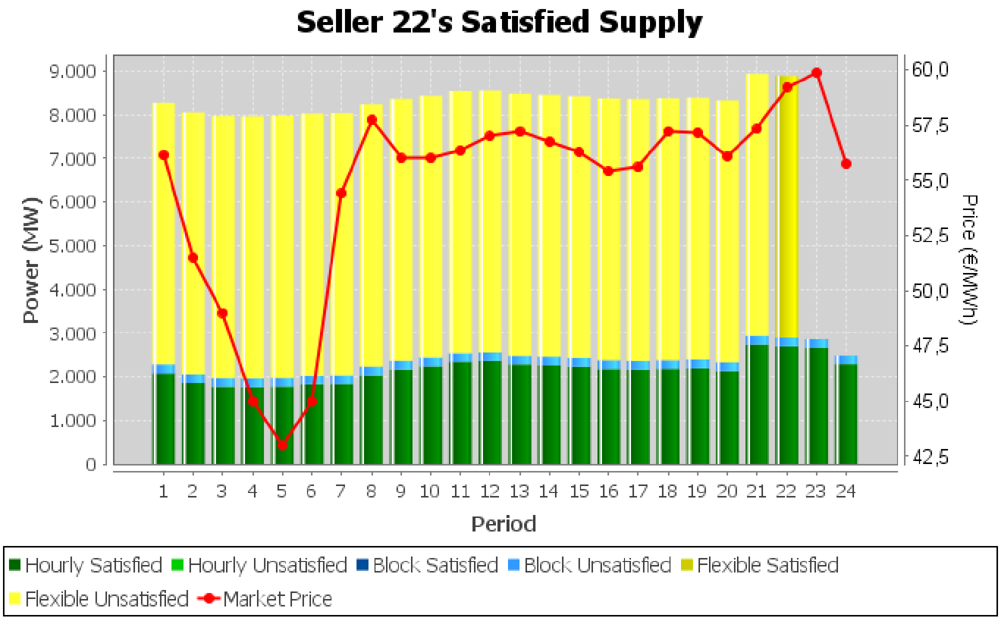


Figure 4.14 - Market results of Seller 22 when participating in the Elspot market mechanism, using block and flexible orders.

As can be seen by the graph of Figure 4.14, the three flexible offers are accepted in period 22, being only the block orders unsatisfied in all of the 24 hourly periods. As mentioned before, the condition for the acceptance of each (or all) flexible offer(s) is not only the proposed bid price, but also the maximization of the overall socioeconomic welfare of the market session, from the market operator's perspective.

Comparing the results of Seller 22 when participating in each one of the three markets, it is possible to observe that it is vital for an agent to have a full understanding of all the different conditions that each market presents. The possibility of using different types of offers, such as complex conditions, flexible and block orders can make a colossal difference both in an individual player's profits, and also in the overall SW of the market. The flexible orders allow a player to sell an extra volume of energy, at a higher price, in hours when that energy is most demanded. By defining a lower price for a block order, a player can sell a predetermined amount of energy throughout the whole market session. In that case, the risk is not very high. However, if the player tries to maximize its profit, by setting a higher price, such as Seller 22 did when participating in the EPEX SPOT market, the risk of the whole block being rejected increases because of the *fill-or-kill* condition.

The use of the proposed ontology, which defines the characteristics and specifications of each different market, allows inferring market rules from the contained information. Taking these rules into account, behaviours can be modelled and adapted. In this case study, Seller 22 has used block orders in its participation in the EPEX SPOT market. These block orders are not available in MIBEL, however, the *Indivisibility* condition that is supported by MIBEL, allows specifying a similar behaviour, as it forces the total amount of offered power to be accepted, otherwise, no power will be sold. This is similar to the *fill-or-kill* condition of the block orders. The inference on the information contained in the ontology allows players to use similar behaviours in different markets, taking advantage on the opportunities and particularities of each market.

Besides the fundamental role of the developed ontologies for the possibility of conducting this type of studies, the restructuring process of MASCEM has also enabled the inclusion of different types of markets, with different characteristics and particularities. Moreover, the four presented scenarios have been executed simultaneously, which was not possible before MASCEM's restructuring. Using the restructured simulator and making use of its novel ontologies, it is now possible to undertake advanced simulation studies, including different market types and players from very different natures.

4.3 Case Study 2 – AiD-EM decision support

This case study has the purpose of demonstrating the interoperability between MASCEM and AiD-EM [Pinto *et al.*, 2015a], the multi-agent decision support system for EM negotiations. Once again, the scenario was created using RealScen [Teixeira *et al.*, 2014], based on data extracted by the automatic data extraction tool [Pereira *et al.*, 2014]. The data used to create this simulation scenario considers real data of all Portuguese and Spanish market participants, a total of 1428 players. With this information it is possible to represent the key players of the Iberian market, MIBEL [OMIE, 2015].

The representation of MIBEL is done by considering 110 players. From Player 1 to Player 55 buyer agents are represented, being the remaining the seller agents. In this scenario only Player 56 (seller agent) uses AiD-EM's decision support, in an attempt to maximize its profits. In this scenario only the day-ahead (or spot) market is considered, consisting in 24 hourly periods, for the day 18th February, 2015. Since this scenario only considers one simulation day, the advantage of using AiD-EM's decision support is not highlighted in the present case study, once its learning is only effective from the second simulation day.

At the beginning of the simulation, MASCEM's Main Agent reads the input data and generates the knowledge bases (KB) – represented in RDF – of each agent. After the creation of the agents, each one receives a message with its respective KB. Since this has already been shown in the previous case study, it will not be presented here. This case study will highlight the communications process between MASCEM and AiD-EM.

After the market operator sends the call for proposals to all the registered players, players gather the necessary information, by querying their KB, in order to submit their proposals to the market operator. Player 56 also prepares its proposal, but before submitting it to the market operator, it requests AiD-EM's support by sending a request message to AiD-EM's Main Agent.

Figure 4.15 presents the request for support message sent by Player 56 to the AiD-EM Main Agent.

```xml
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:aid="http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl#"
4   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
5   xmlns:owl="http://www.w3.org/2002/07/owl#"
6   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
7   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
8   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
9   xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
10   <rdf:Description rdf:about="electricity-markets.owl#iPlayer 56">
11     <aid:hasRequest rdf:resource="aid-em.owl#iRequest"/>
12     <emo:name>Player 56</emo:name>
13     <rdf:type rdf:resource="electricity-markets.owl#Player"/>
14   </rdf:Description>
15   <rdf:Description rdf:about="aid-em.owl#">
16     <owl:imports rdf:resource="aid-em.owl#"/>
17     <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#Ontology"/>
18   </rdf:Description>
19   <rdf:Description rdf:about="aid-em.owl#iRequest">
20     <aid:message>Need decision support</aid:message>
21     <rdf:type rdf:resource="aid-em.owl#Request"/>
22   </rdf:Description>
23 </rdf:RDF>
```

Figure 4.15 - Player 56's request for support

As it is possible to observe from Figure 4.15, the request message sent by Player 56 imports concepts from the *aid-em.owl* ontology (from line 15 to 18) which, in turn, imports concepts from the *electricity-markets.owl* ontology. The sent message identifies the player requesting for support (between lines 10 and 14) and also includes a simple text message of type *aid-em.owl#Request* (lines 19 to 22). This type of message informs the AiD-EM Main Agent that Player 56 is requesting for support.

After receiving the request for support, the AiD-EM Main Agent redirects Player 56's request to a dedicated AiD-EM Manager Agent. This will be the agent that from this point on will aid Player 56 on his needs for support in the market.

The AiD-EM Manager Agent starts by informing Player 56 about which types of market and strategies are available for decision support. AiD-EM provides strategies for the decision support of spot markets (day-ahead/intraday) and bilateral contracts. It also offers the portfolio optimization methodology, which, at every moment, choses the most advantageous market types for the player to negotiate.

Figure 4.16 shows a snippet of the message sent by the AiD-EM Manager Agent to Player 56. The complete version is available online[20]. Analysing Figure 4.16 it is possible to verify the description of some of the various strategies available, such as: *GameTheory* (from line 19 to

[20] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/2/#rdf-16

line 21), *SimpleMetalearner* (between lines 34 and 36) and *SVM* (from line 37 to 39). After receiving the available strategies for decision support, Player 56 chooses, from all the available strategies, the ones that best fit its needs.


```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:aid="http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl#"
4   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
5   xmlns:owl="http://www.w3.org/2002/07/owl#"
6   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
7   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
8   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
9   xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
10    <rdf:Description rdf:about="aid-em.owl#iLinearRegression3">
11      <rdf:type rdf:resource="aid-em.owl#LinearRegression3"/>
12    </rdf:Description>
13    <rdf:Description rdf:about="aid-em.owl#iSimpleRLA">
14      <rdf:type rdf:resource="aid-em.owl#SimpleRLA"/>
15    </rdf:Description>
16    <rdf:Description rdf:about="aid-em.owl#iAverage3">
17      <rdf:type rdf:resource="aid-em.owl#Average3"/>
18    </rdf:Description>
19    <rdf:Description rdf:about="aid-em.owl#iGameTheory">
20      <rdf:type rdf:resource="aid-em.owl#GameTheory"/>
21    </rdf:Description>
22    <rdf:Description rdf:about="aid-em.owl#iErrorTheoryA">
23      <rdf:type rdf:resource="aid-em.owl#ErrorTheoryA"/>
24    </rdf:Description>
25    <rdf:Description rdf:about="aid-em.owl#iDeterminismTheory">
26      <rdf:type rdf:resource="aid-em.owl#DeterminismTheory"/>
27    </rdf:Description>
28    <rdf:Description rdf:about="aid-em.owl#iBilat">
29      <rdf:type rdf:resource="aid-em.owl#Bilat"/>
30    </rdf:Description>
31    <rdf:Description rdf:about="aid-em.owl#iComposedGoalDirected">
32      <rdf:type rdf:resource="aid-em.owl#ComposedGoalDirected"/>
33    </rdf:Description>
34    <rdf:Description rdf:about="aid-em.owl#iSimpleMetalearner">
35      <rdf:type rdf:resource="aid-em.owl#SimpleMetalearner"/>
36    </rdf:Description>
37    <rdf:Description rdf:about="aid-em.owl#iSVM">
38      <rdf:type rdf:resource="aid-em.owl#SVM"/>
39    </rdf:Description>
```


Figure 4.16 - AiD-EM Manager Agent response to Player 56's request for proposal

In this case, Player 56 is only interested in using the spot market strategies since it will not participate in bilateral contacts. For this reason it also ignores the portfolio optimization.

Therefore, Player 56 chooses to use only ALBidS [Pinto *et al.*, 2015a] with the market strategies: *Average 1*, *Average 2*, *Average 3*, *Average 4*, *Linear Regression 1*, *Linear Regression 2*, *Linear Regression 3*, *Linear Regression 4*, *ANN* and *Weighted Metalearner*; and the reinforcement learning algorithm (RLA) *SimpleRLA*.

Along with the choice of strategies, Player 56 also sends to AiD-EM Manager Agent its offers for the 24 hourly periods. Figure 4.17 presents a snippet of the selection sent by Player 56 to the AiD-EM Manager Agent. A full observation of the RDF content can be made online[21].

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:aid="http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl#"
4   xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
5   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
6   xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
7   xmlns:owl="http://www.w3.org/2002/07/owl#"
8   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
9   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
10  xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
11  xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
12   <rdf:Description rdf:about="mibel.owl#iPower1-P24-DayAheadSession2015-02-18-0">
13     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">50.0
       </emo:value>
14     <emo:unit>MW</emo:unit>
15     <rdf:type rdf:resource="electricity-markets.owl#Power"/>
16   </rdf:Description>
17   <rdf:Description rdf:about="mibel.owl#iPower1-P7-DayAheadSession2015-02-18-0">
18     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">50.0
       </emo:value>
19     <emo:unit>MW</emo:unit>
20     <rdf:type rdf:resource="electricity-markets.owl#Power"/>
21   </rdf:Description>
22   <rdf:Description rdf:about="mibel.owl#iOffer1-P6-DayAheadSession2015-02-18-0">
23     <emo:hasPrice rdf:resource="mibel.owl#iPrice1-P6-DayAheadSession2015-02-18-0"/>
24     <emo:hasPower rdf:resource="mibel.owl#iPower1-P6-DayAheadSession2015-02-18-0"/>
25     <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">1
       </emo:number>
26     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       3736978764748093358</emo:id>
27     <rdf:type rdf:resource="electricity-markets.owl#Offer"/>
28   </rdf:Description>
29   <rdf:Description rdf:about="aid-em.owl#iLinearRegression3">
30     <rdf:type rdf:resource="aid-em.owl#LinearRegression3"/>
31   </rdf:Description>
32   <rdf:Description rdf:about="mibel.owl#iPrice1-P8-DayAheadSession2015-02-18-0">
33     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
34     <emo:unit>EUR</emo:unit>
35     <rdf:type rdf:resource="electricity-markets.owl#Price"/>
36   </rdf:Description>
```

Figure 4.17 - Player 56's strategies selection

In a brief analysis to Figure 4.17 it is possible to verify the choice of the market strategy *LinearRegression3* (from line 29 to line 31), together with the definition of available offers for the day-ahead session of the daily market (the remaining lines). The *LinearRegression3* is just one of the strategies selected by this player. The remaining are available on the internet location mentioned above.

[21] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/2/#rdf-17

The AiD-EM Manager agent receives the strategies selection and the proposal from Player 56. After running the selected algorithms, it answers to Player 56 with the prices suggestion, taking into account the simulation date and type of session. Figure 4.18 shows a snippet of the answer sent to Player 56. A full version of the message content is available online[22]. In the fragment below it is possible to see the price suggested for the hourly period 8 (between lines 28 and 32).

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
4   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
5   xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
6   xmlns:owl="http://www.w3.org/2002/07/owl#"
7   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
8   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
9   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
10  xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
11   <rdf:Description rdf:about="mibel.owl#iPower1-P24-DayAheadSession2015-02-18-0">
12     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">50.0
       </emo:value>
13     <emo:unit>MW</emo:unit>
14     <rdf:type rdf:resource="electricity-markets.owl#Power"/>
15   </rdf:Description>
16   <rdf:Description rdf:about="mibel.owl#iPower1-P7-DayAheadSession2015-02-18-0">
17     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">50.0
       </emo:value>
18     <emo:unit>MW</emo:unit>
19     <rdf:type rdf:resource="electricity-markets.owl#Power"/>
20   </rdf:Description>
21   <rdf:Description rdf:about="mibel.owl#iOffer1-P6-DayAheadSession2015-02-18-0">
22     <emo:hasPrice rdf:resource="mibel.owl#iPrice1-P6-DayAheadSession2015-02-18-0"/>
23     <emo:hasPower rdf:resource="mibel.owl#iPower1-P6-DayAheadSession2015-02-18-0"/>
24     <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">1
       </emo:number>
25     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       3736978764748093358</emo:id>
26     <rdf:type rdf:resource="electricity-markets.owl#Offer"/>
27   </rdf:Description>
28   <rdf:Description rdf:about="mibel.owl#iPrice1-P8-DayAheadSession2015-02-18-0">
29     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">
       53.2353595017074</emo:value>
30     <emo:unit>EUR</emo:unit>
31     <rdf:type rdf:resource="electricity-markets.owl#Price"/>
32   </rdf:Description>
33   <rdf:Description rdf:about="mibel.owl#iOffer1-P19-DayAheadSession2015-02-18-0">
34     <emo:hasPrice rdf:resource="mibel.owl#iPrice1-P19-DayAheadSession2015-02-18-0"/>
35     <emo:hasPower rdf:resource="mibel.owl#iPower1-P19-DayAheadSession2015-02-18-0"/>
36     <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">1
       </emo:number>
37     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       3608442998440978729</emo:id>
38     <rdf:type rdf:resource="electricity-markets.owl#Offer"/>
39   </rdf:Description>
```

Figure 4.18 - AiD-EM Manager Agent Proposal suggestion for Player 56

[22] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/2/#rdf-18

After receiving the action proposal from AiD-EM's Manager Agent, Player 56 sends its proposal, with the suggested prices, to the Market Operator. After validating all incoming proposals, the Market Operator executes the market session and sends the results to the participant players. As stated before, only the RDF concerning the interoperability of MASCEM with AiD-EM is shown in this case study. On one hand, to prevent excessive extension of the document, and also because in the previous case study examples of the remaining communications have already been shown.

In order to demonstrate the impact of using AiD-EM decision support, the outcomes of Player 56 are analysed. This player takes advantage of AiD-EM's services trying to influence the market price, with the purpose of achieving higher profits. Figure 4.19 illustrates the results of Player 56 in the day-ahead market session of the Iberian market.

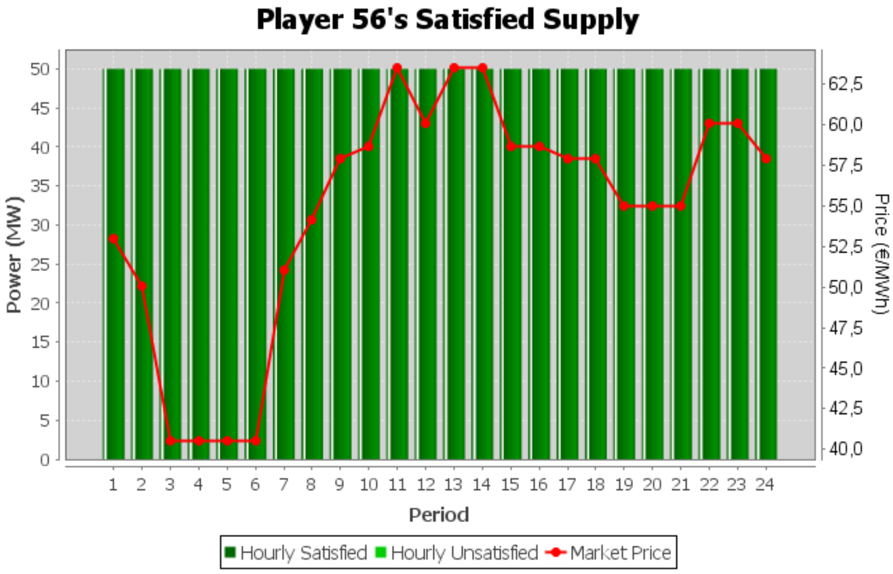


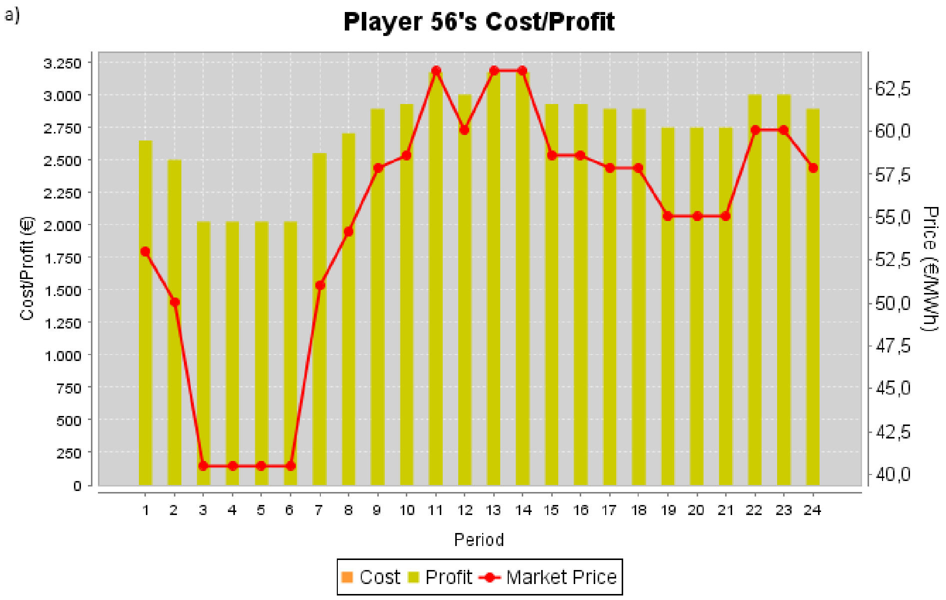
Figure 4.19 - Player 56's results

As it is possible to observe in Figure 4.19, Player 56 was able to sell all its available energy. When comparing the established market price with the prices offered by this player, it can be seen that the prices offered by Player 56 are always below the achieved market price, although in some periods they are very close. Table 4.1 compares the prices presented by Player 56 with the resultant market prices.

The bid prices suggested by the AiD-EM decision support were very close to the achieved market prices. However, since none of the market prices was defined by this player, it could never directly influence the market's outcome, in order to increase its profits. Figure 4.20 illustrates the profits of Player 56 a) with and b) without AiD-EM's support for each period of the market during the considered simulation day.

Table 4.1 - Comparison between the price offered by Player 56 and the market price

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Offered Price (€)	29.10	44.46	39.75	40.25	40.51	40.50	20.50	53.24
Market Price (€)	53.00	50.06	40.53	40.53	40.53	40.53	51.02	54.13
Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Offered Price (€)	57.10	51.71	63.29	59.77	47.58	50.98	46.13	57.76
Market Price (€)	57.88	58.64	63.51	60.09	63.51	63.51	58.64	58.64
Period	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Offered Price (€)	57.51	23.80	54.53	54.42	54.45	59.61	59.72	53.35
Market Price (€)	57.88	57.88	55.03	55.03	55.03	60.09	60.09	57.88



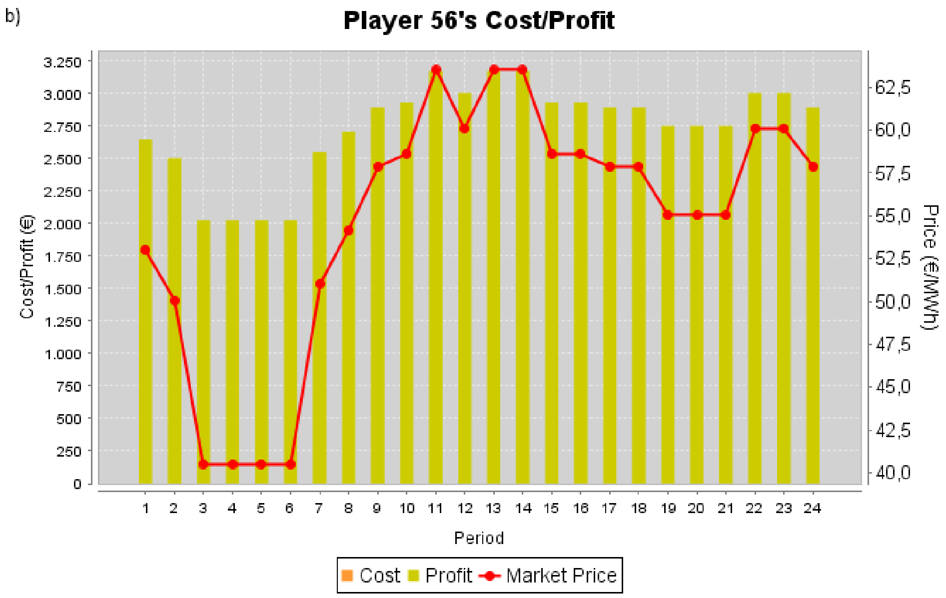


Figure 4.20 - Player 56's profits a) with and b) without AiD-EM's decision support

Player 56 had an approximate profit of €65683.00. If this player had defined the market price at some or all of the trading periods, two possible scenarios could arise: a) on an optimistic side, the player would have been able to increase its profits even if it had not sold all the energy available in the market; b) on the other hand, if the player was not able to sell enough power, even if he had set the market prices in all periods, profits would be lower than the achieved.

The results achieved by the player with and without the use of AiD-EM have been the same because of, in the first instance, the small dimension of the supported player, whose amount of negotiated power is not enough to allow it to have any influence on the market outcomes, even when changing its negotiation behaviour; and secondly because the simulation only concerns one day, and as discussed in [Pinto *et al.*, 2014b], AiD-EM requires the execution of several days to be able to achieve advantageous learning results. The number of iterations is essential for the different strategies to be able to understand the environment and adapt themselves in order to suggest the most adequate actions for the supported player to perform.

Using the publicly available AiD-EM ontology, any player participating in a spot electricity market and/or bilateral contract is able to request AiD-EM's assistance taking advantage of its decision support in the prices definition for the respective negotiation. Being an independent MAS, AiD-EM was designed to support not only MASCEM's players, but also players from other wholesale EM simulators.

In this case study Player 56 decided to use AiD-EM's aid in order to maximize its profits. As shown, this player did not have a direct influence on the definition of the market prices of each period. However, a more risky approach could have led this player to less positive results, if it could not negotiate enough energy to cover the currently achieved results.

4.4 Case Study 3 – MASGriP participation in the market

This third case study demonstrates the interoperability between MASCEM and MASGriP [Oliveira *et al.*, 2012] and also the interoperability between MASGriP and AiD-EM [Pinto *et al.*, 2015a]. The case study is divided into two subsections: MASGriP – Smart Grid participation in the market; and MASGriP – AiD-EM supporting Smart Grid's decision-making in the market.

This case study is focused on the Iberian electricity market which is composed by Portugal and Spain areas, including offers from all players of the day-ahead market concerning the 1st January, 2012. The purchase and sale offers of each player are provided by MIBEL's market operator OMIE (*Operador del Mercado Ibérico de Energía*) [OMIE, 2014]. The data was extracted with the extraction tool [Pereira *et al.*, 2014] and regards 826 distinct players, from which 714 are sellers and the remaining 112 are buyers. From the sellers, 397 have wind power generation in their portfolio mix. A windy day was chosen with the wind reaching very high speeds, which leads to a much greater production offer than the demand.

For the analysis of this case study, special attention is paid to the agent SG 821. SG 821 is defined as a MASGriP SG whose production is only based on wind, *i.e.*, all the generator players use wind production. In this case study only communications concerning the interoperability between MASCEM and MASGriP and MASGriP with AiD-EM are considered, since the remaining have already been presented in the previous case studies.

4.4.1 MASGriP – Smart Grid participation in the market

In the first scenario of this case study, SG 821 participates in the day-ahead market with 75% of its total production, reserving the remaining 25% to participate in the first session of MIBEL's intraday market.

4.4.1.1 Day-ahead market simulation

After receiving the call for proposal sent by MASCEM's Market Operator for the daily market, player SG 821 gathers all the necessary information from its aggregated players, in order to submit a proposal to participate in the market.

From the point of view of the market operator, SG 821 is a common player of MASCEM, being the communications exchanged by these two agents similar to those exchanged with MASCEM's native players. Figure 4.21 features the call for proposal sent by MASCEM's Market Operator to all registered players.

By observing Figure 4.21 it is possible to see the definition of a call for proposal (from line 36 to line 39) for the electricity market named *MIBEL* (between lines 31 and 35), with market type *SPOT* (from line 11 to 17), operated by the *OMIE* market operator (defined between lines 40 and 43), with a single day-ahead session (visible from line 18 to line 25) defining 24 hourly periods (see line 21) and 25 as the maximum number of fractions (line 20) for the 1st January, 2012 (in line 24).

After gathering all the required information, SG 821 generates its market proposal and sends it to the OMIE market operator. Figure 4.22 presents a snippet of the proposal sent by SG 821 to the OMIE market operator. A full representation of the proposal is available online[23].

Figure 4.22 shows the definition of a *Bid* placed in *Period* 1 (visible from line 21 to line 51), of transaction type *sell* (see line 30), for which 25 *Offer* fractions are defined (in lines 22 to 25; 27 to 29; 31 and 32; and 34 to 49).

After receiving all the proposals or after ending the available time for the reception of bids, the market operator validates the proposals and executes the session of the daily market. At the end of the market simulation, it converts the market results' of each player into RDF and sends

[23] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/3/1/1/#rdf-22

them to the respective player. The RDF that contains the market results of SG 821 is shown in Figure 4.23. The full RDF results of SG 821 are available online[24].

```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="mibel.owl#iMT-SPOT">
    <rdf:type rdf:resource="mibel.owl#Day-Ahead"/>
    <emo:isOperatedBy rdf:resource="electricity-markets.owl#iMO-OMIE"/>
    <emo:hasSession rdf:resource="mibel.owl#iDayAheadSession2012-01-01-0"/>
    <emo:name>SPOT</emo:name>
    <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">2496624663368592042</emo:id>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iDayAheadSession2012-01-01-0">
    <rdf:type rdf:resource="mibel.owl#DayAheadSession"/>
    <emo:maxNumberOfFractions rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">25</emo:maxNumberOfFractions>
    <emo:numberOfPeriods rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">24</emo:numberOfPeriods>
    <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">0</emo:number>
    <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">9095887563784764489</emo:id>
    <emo:date rdf:datatype="http://www.w3.org/2001/XMLSchema#date">2012-01-01</emo:date>
  </rdf:Description>
  <rdf:Description rdf:about="call-for-proposal.owl#">
    <owl:imports rdf:resource="mibel.owl#"/>
    <owl:imports rdf:resource="call-for-proposal.owl#"/>
    <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#Ontology"/>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iM-MIBEL">
    <emo:hasMarketType rdf:resource="mibel.owl#iMT-SPOT"/>
    <emo:name>MIBEL</emo:name>
    <rdf:type rdf:resource="mibel.owl#MIBEL"/>
  </rdf:Description>
  <rdf:Description rdf:about="call-for-proposal.owl#iCFP-DayAheadSession2012-01-01-0">
    <cfp:forElectricityMarket rdf:resource="mibel.owl#iM-MIBEL"/>
    <rdf:type rdf:resource="call-for-proposal.owl#CallForProposal"/>
  </rdf:Description>
  <rdf:Description rdf:about="electricity-markets.owl#iMO-OMIE">
    <emo:name>OMIE</emo:name>
    <rdf:type rdf:resource="electricity-markets.owl#MarketOperator"/>
  </rdf:Description>
</rdf:RDF>
```

Figure 4.21 - OMIE Market Operator's Spot CfP RDF

[24] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/3/1/1/#rdf-23

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="mibel.owl#iPower10-P20-DayAheadSession2012-01-01-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
    <emo:unit>MW</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Power"/>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iPower17-P7-DayAheadSession2012-01-01-0">
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
    <emo:unit>MW</emo:unit>
    <rdf:type rdf:resource="electricity-markets.owl#Power"/>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iBid1-DayAheadSession2012-01-01-0">
    <emo:hasOffer rdf:resource="mibel.owl#iOffer3-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer12-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer22-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer23-P1-DayAheadSession2012-01-01-0"/>
    <emo:placedByPlayer rdf:resource="mibel.owl#iSG_821"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer11-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer18-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer1-P1-DayAheadSession2012-01-01-0"/>
    <emo:transactionType>sell</emo:transactionType>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer2-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer15-P1-DayAheadSession2012-01-01-0"/>
    <emo:placedInSinglePeriod rdf:resource=
     "mibel.owl#iPeriod1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer5-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer21-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer9-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer6-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer20-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer16-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer8-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer24-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer14-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer19-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer13-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer25-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer17-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer4-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer7-P1-DayAheadSession2012-01-01-0"/>
    <emo:hasOffer rdf:resource="mibel.owl#iOffer10-P1-DayAheadSession2012-01-01-0"/>
    <rdf:type rdf:resource="electricity-markets.owl#Bid"/>
  </rdf:Description>
```


Figure 4.22 - Spot proposal presented by SG 821

By analysing the last lines of the RDF excerpt from Figure 4.23, it is possible to see the definition of the traded power for period 11 with an approximate value of *976.65* and unit *MW* (between lines 29 and 33). The results of player SG 821 in the day-ahead market can also be visualized graphically in Figure 4.24.

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:emr="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl#"
 xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-24">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-HourlyResult-24"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-HourlyResult-24"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">24
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
  </rdf:Description>
  <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-12">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-HourlyResult-12"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-HourlyResult-12"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">12
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
  </rdf:Description>
  <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-20">
    <emo:hasPrice rdf:resource=
    "electricity-markets-results.owl#iMarketPrice-HourlyResult-20"/>
    <emo:hasPower rdf:resource=
    "electricity-markets-results.owl#iTradedPower-HourlyResult-20"/>
    <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">20
    </emr:periodNumber>
    <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
  </rdf:Description>
  <rdf:Description rdf:about=
  "electricity-markets-results.owl#iTradedPower-HourlyResult-11">
    <emo:unit>MW</emo:unit>
    <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">
    976.6500000000001</emo:value>
    <rdf:type rdf:resource="electricity-markets-results.owl#TradedPower"/>
  </rdf:Description>
```


Figure 4.23 - Results achieved by SG 821 in day-ahead pool

Analysing the results of SG 821 from Figure 4.24, it is visible that all of the energy available for sale in the market has been negotiated. As the player's production is wind based, he has offered a 0 price in each period, in order to dispatch all of the available generation.

Making use of MASCEM's public ontology, MASGriP players have the opportunity to participate in the simulations of the wholesale EM of MASCEM. The publicly available ontology of MASCEM allows players from any MAS, or individuals, to participate in its simulations, like any player of the own MASCEM. Therefore, through MASCEM's ontology, the interoperability between MASCEM and agents from external systems willing to participate in the simulations of EM as market players is enabled.

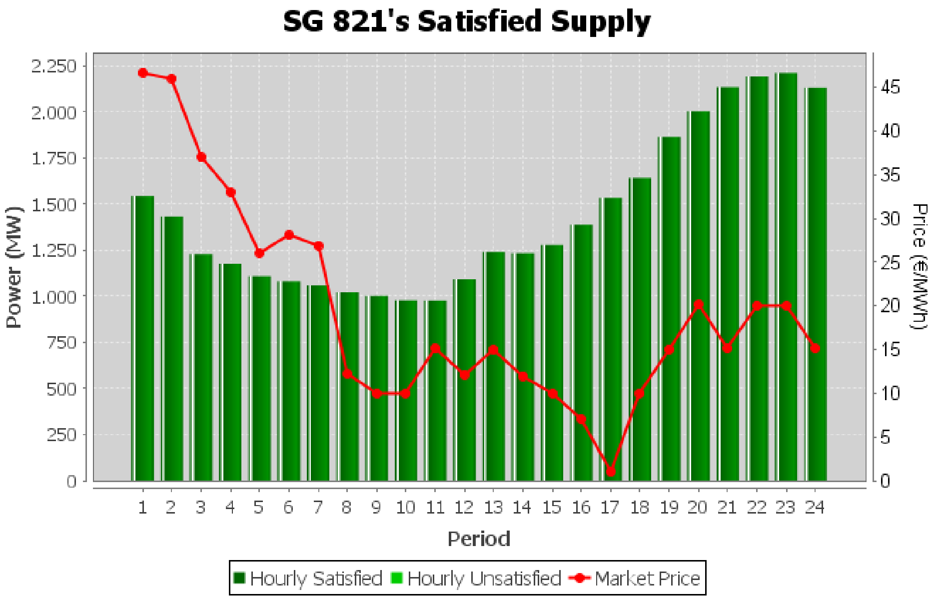


Figure 4.24 - SG 821's results

4.4.1.2 Intraday market simulation

Once the day-ahead market negotiations are finished, each player reviews its results and decides whether it will or not participate in the intraday market, in order to meet the required adjustments of the feasible daily program and of the last scheduling. Only agents who have not sold all their energy in the daily market and/or kept power strategically to negotiate later, like SG 821, will participate in the intraday market. Therefore, in the second scenario of this case study, only 307 agents participate in the intraday market, from these 269 are sellers and the remaining 38 are buyer agents. For this scenario, only the first session of the intraday market is considered, in order to facilitate the interpretation of results.

The intraday market starts with the call for proposal sent by the market operator to the respective players. Figure 4.25 shows the call for proposal received by SG 821 for the first session of the intraday market.

By analysing Figure 4.25 it is possible to see the definition of a call for proposal for the electricity market *MIBEL* (from lines 27 to 31), with market type *INTRADAY* (between lines 16 and 22), operated by the market operator *OMIE* (line 40 to line 43), concerning the first session (session's "*number*" equals to 0 in line 36) of the intraday market (from line 32 to line 39), considering 27 hourly periods (the 24 hourly periods of the following day: 1st January, 2012, and the last 3 periods of the current day: 31st December, 2011 [OMIE, 2015] – see line 35). Since this study concerns the day of January 1st, 2012, the player does not make any offer for the 3 first periods of this session.

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="call-for-proposal.owl#">
    <owl:imports rdf:resource="mibel.owl#"/>
    <owl:imports rdf:resource="call-for-proposal.owl#"/>
    <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#Ontology"/>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iMT-INTRADAY">
    <rdf:type rdf:resource="mibel.owl#Intraday"/>
    <emo:isOperatedBy rdf:resource="electricity-markets.owl#iMO-OMIE"/>
    <emo:hasSession rdf:resource="mibel.owl#iIntradaySession2012-01-01-0"/>
    <emo:name>INTRADAY</emo:name>
    <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
    3335641700172420905</emo:id>
  </rdf:Description>
  <rdf:Description rdf:about="call-for-proposal.owl#iCFP-IntradaySession2012-01-01-0">
    <cfp:forElectricityMarket rdf:resource="mibel.owl#iM-MIBEL"/>
    <rdf:type rdf:resource="call-for-proposal.owl#CallForProposal"/>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iM-MIBEL">
    <emo:hasMarketType rdf:resource="mibel.owl#iMT-INTRADAY"/>
    <emo:name>MIBEL</emo:name>
    <rdf:type rdf:resource="mibel.owl#MIBEL"/>
  </rdf:Description>
  <rdf:Description rdf:about="mibel.owl#iIntradaySession2012-01-01-0">
    <rdf:type rdf:resource="mibel.owl#IntradaySession"/>
    <emo:maxNumberOfFractions rdf:datatype=
    "http://www.w3.org/2001/XMLSchema#unsignedInt">25</emo:maxNumberOfFractions>
    <emo:numberOfPeriods rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">
    27</emo:numberOfPeriods>
    <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">0
    </emo:number>
    <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
    3451408283044059088</emo:id>
    <emo:date rdf:datatype="http://www.w3.org/2001/XMLSchema#date">2012-01-01
    </emo:date>
  </rdf:Description>
  <rdf:Description rdf:about="electricity-markets.owl#iMO-OMIE">
    <emo:name>OMIE</emo:name>
    <rdf:type rdf:resource="electricity-markets.owl#MarketOperator"/>
  </rdf:Description>
</rdf:RDF>
```

Figure 4.25 - OMIE Market Operator's Intraday CfP RDF

After completing the generation of its proposal, the player SG 821 sends it to the market operator, *MIBEL*. An excerpt from the proposal sent by the player is shown in Figure 4.26. A full version of this player's proposal is available online[25].

[25] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/3/1/2/#rdf-26

```
1   <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2   <rdf:RDF
3    xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
     xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
4    xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
5    xmlns:owl="http://www.w3.org/2002/07/owl#"
6    xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
7    xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
8    xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
9    xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
10    <rdf:Description rdf:about="mibel.owl#iPrice17-P6-IntradaySession2012-01-01-0">
11      <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
12      <emo:unit>EUR</emo:unit>
13      <rdf:type rdf:resource="electricity-markets.owl#Price"/>
14    </rdf:Description>
15    <rdf:Description rdf:about="mibel.owl#iOffer5-P1-IntradaySession2012-01-01-0">
16      <emo:hasPrice rdf:resource="mibel.owl#iPrice5-P1-IntradaySession2012-01-01-0"/>
17      <emo:hasPower rdf:resource="mibel.owl#iPower5-P1-IntradaySession2012-01-01-0"/>
18      <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">5
        </emo:number>
19      <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
        1737094209368063022</emo:id>
20      <rdf:type rdf:resource="electricity-markets.owl#Offer"/>
21    </rdf:Description>
22    <rdf:Description rdf:about="mibel.owl#iPrice21-P22-IntradaySession2012-01-01-0">
23      <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
24      <emo:unit>EUR</emo:unit>
25      <rdf:type rdf:resource="electricity-markets.owl#Price"/>
26    </rdf:Description>
27    <rdf:Description rdf:about="mibel.owl#iPrice16-P24-IntradaySession2012-01-01-0">
28      <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
29      <emo:unit>EUR</emo:unit>
30      <rdf:type rdf:resource="electricity-markets.owl#Price"/>
31    </rdf:Description>
32    <rdf:Description rdf:about="mibel.owl#iPrice1-P25-IntradaySession2012-01-01-0">
33      <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">0.0</emo:value>
34      <emo:unit>EUR</emo:unit>
35      <rdf:type rdf:resource="electricity-markets.owl#Price"/>
36    </rdf:Description>
37    <rdf:Description rdf:about="mibel.owl#iOffer18-P19-IntradaySession2012-01-01-0">
38      <emo:hasPrice rdf:resource="mibel.owl#iPrice18-P19-IntradaySession2012-01-01-0"/>
39      <emo:hasPower rdf:resource="mibel.owl#iPower18-P19-IntradaySession2012-01-01-0"/>
40      <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">18
        </emo:number>
41      <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
        6084189378339812529</emo:id>
42      <rdf:type rdf:resource="electricity-markets.owl#Offer"/>
43    </rdf:Description>
```


Figure 4.26 - Intraday proposal presented by SG 821

For the intraday market, SG 821 considers the reserve of 25% of the generated energy, including also the unsold energy of the day-ahead market. With this strategy, agent SG 821 tries to be able to sell the remaining power at a higher price than in the spot market. This player expects that buyer agents in intraday market are willing to raise the value of their offerings, to ensure the purchase of the required energy. Although the excerpt from Figure 4.26 shows a rather limited version of the SG 821 proposal to the intraday market, it allows identifying the definition of offers and prices for some periods (from line 10 to line 43).

After receiving and validating the proposals, the market operator carries out the execution of the first session of the intraday market. At the end of the simulation, the market operator converts the results into RDF so that it can send them to the participant players. An extract of SG 821's RDF results is shown in Figure 4.27. A full version is available for consultation online[26].

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
4   xmlns:emr=
    "http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets-results.owl#"
5   xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
6   xmlns:owl="http://www.w3.org/2002/07/owl#"
7   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
8   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
9   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
10  xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
11   <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-24">
12     <emo:hasPrice rdf:resource=
       "electricity-markets-results.owl#iMarketPrice-HourlyResult-24"/>
13     <emo:hasPower rdf:resource=
       "electricity-markets-results.owl#iTradedPower-HourlyResult-24"/>
14     <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">24
       </emr:periodNumber>
15     <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
16   </rdf:Description>
17   <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-12">
18     <emo:hasPrice rdf:resource=
       "electricity-markets-results.owl#iMarketPrice-HourlyResult-12"/>
19     <emo:hasPower rdf:resource=
       "electricity-markets-results.owl#iTradedPower-HourlyResult-12"/>
20     <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">12
       </emr:periodNumber>
21     <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
22   </rdf:Description>
23   <rdf:Description rdf:about="electricity-markets-results.owl#iHourlyResult-20">
24     <emo:hasPrice rdf:resource=
       "electricity-markets-results.owl#iMarketPrice-HourlyResult-20"/>
25     <emo:hasPower rdf:resource=
       "electricity-markets-results.owl#iTradedPower-HourlyResult-20"/>
26     <emr:periodNumber rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">20
       </emr:periodNumber>
27     <rdf:type rdf:resource="electricity-markets-results.owl#HourlyResult"/>
28   </rdf:Description>
```

Figure 4.27 - SG 821's intraday results

By analysing the excerpt of the results achieved by agent SG 821, provided in Figure 4.27, it is possible to see the definition of *HourlyResult*s for periods 12 (from line 17 to line 22), 20 (between lines 23 and 28) and 24 (from lines 11 to 16).

Figure 4.28 shows a graphical representation of agent SG 821's results in the first session of the intraday market. Due to a very high wind generation, market prices tend to decline

[26] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/3/1/2/#rdf-27

considerably, even assuming the value of 0 €/MWh in some periods, as can be seen by Figure 4.28.

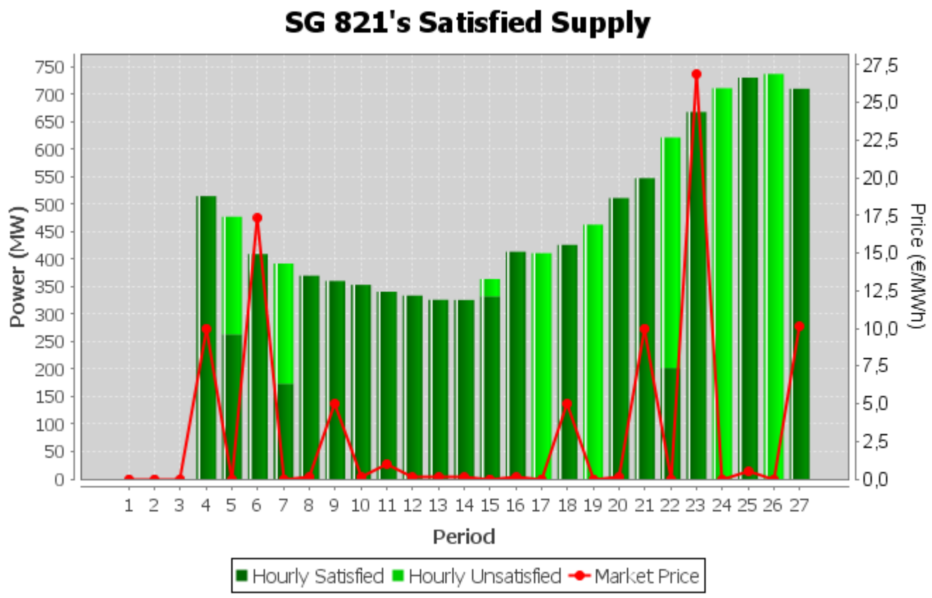


Figure 4.28 - SG 821's results for the first session of intraday market

It is possible to verify that agent SG 821 could not negotiate all the energy available in 8 of the 27 trading periods (periods 5, 7, 15, 17, 19, 22, 24 and 26). From these 8 periods, SG 821 failed to transact any of the available energy in 4 (periods 17, 19, 24 and 26). In the other 4 periods (periods 5, 7, 15 and 22), SG 821 has been able to sell only a partial amount of its available power. This has occurred because the established market price has been equal to the bid price submitted by the player. The tendency for very low market prices is verified throughout the entire intraday market session, with more than half of the trading periods having assumed market prices of 0 €/MWh or very near this value. The absence of power to negotiate during the first 3 trading periods (as they refer to the last three hours of the day prior to the studied simulation day) should also be noticed.

The lack of energy to negotiate during the first 3 trading periods occurs because the considered simulation day is the first simulation day, therefore there is no previous day in the simulation, allowing to renegotiate the last 3 hourly periods of the day.

Figure 4.29 presents the results of the first session of the intraday market from the market operator perspective.

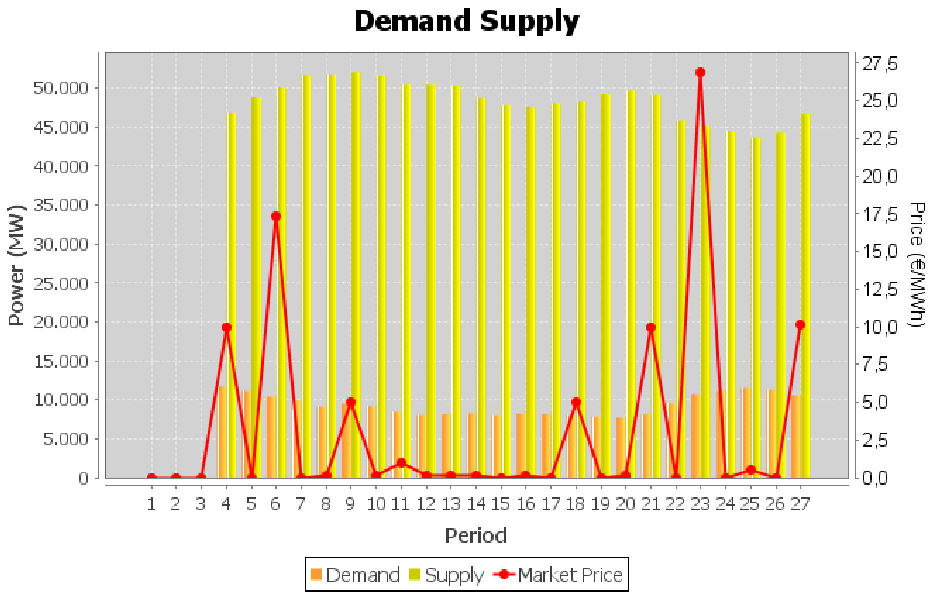


Figure 4.29 - OMIE's results for the first session of the intraday market

The supply is significantly higher than the demand in all trading periods, as it is possible to observe in Figure 4.29. Despite the bid prices proposed by agent SG 821 are always 0 €/MWh, the player is not always able to sell all the available energy. Since it was not the only agent to submit offers with the price of 0 €/MWh, the market operator orders the offers with the same price in order of arrival; which means that this agent did not submit its offers in a timely manner to ensure the complete trading of all its available energy in all periods. In the periods in which this agent negotiated only part of its supply, it was this agent who was located in the intersection of the supply and demand curves of the symmetrical auction mechanism (see subsection 2.2.1.1), so he was the one imposing the market price.

The MASCEM's public ontologies have allowed agent SG 821 of MASGriP to participate in the simulation of the electricity market MIBEL. From the market operator's point of view, the MASGriP agent is viewed as a regular MASCEM player, despite MASGriP being an independent MAS. This type of interactions is shown further in the following simulation, where a scenario in which besides interacting with MASCEM, MASGriP also communicates with AiD-EM, asking for decision support for the definition of bid prices to propose in the market.

4.4.2 MASGriP – AiD-EM supporting Smart Grid's decision-making in the market

In the second scenario of this case study, MASGriP's player SG 821 requests AiD-EM's decision support for the prices definition for the daily market, considering the same simulation day. Only the day-ahead market is simulated, with the same input data from the previous scenario, with the only difference that the player SG 821's prices are defined by AiD-EM agent-based decision support tool.

Since the main objective of this scenario is to demonstrate the interoperability between MASGriP and AiD-EM, only the communications that occur between these two MAS are shown.

The simulation starts with MASCEM's main agent reading the input data and generating the RDF KB of each agent present in the input file. The agents are created and their KB are sent by the MASCEM Main Agent. Right after the user starts the simulation, the market operator creates the respective CfP and sends it to the registered players. In turn, the players gather all their proposals for the respective session of the market, by querying their KB.

Player SG 821 also prepares its proposal, but this time it requests AiD-EM decision support before submitting its proposal to the market operator. Figure 4.30 shows the request message sent by SG 821 to AiD-EM Main Agent.

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:aid="http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl#"
4   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
5   xmlns:owl="http://www.w3.org/2002/07/owl#"
6   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
7   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
8   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
9   xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
10   <rdf:Description rdf:about="electricity-markets.owl#iSG 821">
11     <aid:hasRequest rdf:resource="aid-em.owl#iRequest"/>
12     <emo:name>SG 821</emo:name>
13     <rdf:type rdf:resource="electricity-markets.owl#Player"/>
14   </rdf:Description>
15   <rdf:Description rdf:about="aid-em.owl#">
16     <owl:imports rdf:resource="aid-em.owl#"/>
17     <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#Ontology"/>
18   </rdf:Description>
19   <rdf:Description rdf:about="aid-em.owl#iRequest">
20     <aid:message>Need decision support</aid:message>
21     <rdf:type rdf:resource="aid-em.owl#Request"/>
22   </rdf:Description>
23 </rdf:RDF>
```

Figure 4.30 - SG 821's request for support

As illustrated in Figure 4.30 the sent message identifies the player SG 821 (from line 10 to line 14) requesting for support, including also a simple text message of the type *aid-em.owl#Request* (between lines 19 and 22), informing the AiD-EM's Main Agent that this player is requesting support.

Upon receiving the request for support, the AiD-EM Main Agent assigns a dedicated AiD-EM Manager Agent to help player SG 821 in the market. The Manager Agent begins by communicating the available types of market and corresponding strategies for decision support to player SG 821. Figure 4.31 displays a part of the RDF answer sent by the AiD-EM Manager Agent to SG 821. The complete RDF message is available online[27].

[27] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/3/2/#rdf-31

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:aid="http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl#"
4   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
5   xmlns:owl="http://www.w3.org/2002/07/owl#"
6   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
7   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
8   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
9   xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
10   <rdf:Description rdf:about="aid-em.owl#iSimulatedAnnealing">
11     <rdf:type rdf:resource="aid-em.owl#SimulatedAnnealing"/>
12   </rdf:Description>
13   <rdf:Description rdf:about="aid-em.owl#iGA">
14     <rdf:type rdf:resource="aid-em.owl#GA"/>
15   </rdf:Description>
16   <rdf:Description rdf:about="aid-em.owl#iRothErev">
17     <rdf:type rdf:resource="aid-em.owl#RothErev"/>
18   </rdf:Description>
19   <rdf:Description rdf:about="aid-em.owl#iEPSO">
20     <rdf:type rdf:resource="aid-em.owl#EPSO"/>
21   </rdf:Description>
22   <rdf:Description rdf:about="aid-em.owl#iSimpleRLA">
23     <rdf:type rdf:resource="aid-em.owl#SimpleRLA"/>
24   </rdf:Description>
25   <rdf:Description rdf:about="aid-em.owl#iANN">
26     <rdf:type rdf:resource="aid-em.owl#ANN"/>
27   </rdf:Description>
28   <rdf:Description rdf:about="aid-em.owl#">
29     <owl:imports rdf:resource="aid-em.owl#"/>
30     <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#Ontology"/>
31   </rdf:Description>
32   <rdf:Description rdf:about="aid-em.owl#iGameTheory">
33     <rdf:type rdf:resource="aid-em.owl#GameTheory"/>
34   </rdf:Description>
```

Figure 4.31 - AiD-EM Manager Agent response to SG 821's request for support

By observing Figure 4.31 the definition of some of the available strategies, such as *ANN* (lines 25 to 27) and *GameTheory* (from line 32 to line 34) can be seen.

The following step is for agent SG 821 to select the strategies that better fits its needs, considering the day-ahead market of MIBEL. In this case, SG 821 chooses only strategies that concern the daily market. Together with the selection of strategies, SG 821 also sends its proposal for the 24 periods of the day-ahead market session. A snip of the selection made by SG 821 is illustrated in Figure 4.32. The full RDF content is available online[28].

From Figure 4.32 it is possible to confirm the selection of the tools *ALBidS* (line 26) and *PortfolioOptimization* (line 46); and the use of the strategies *StandardPSO* (line 22), *SVM* (line 25), *SimpleRLA* (line 28), *GameTheory* (line 32), *ANN* (line 34), among others.

[28] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/3/2/#rdf-32

```xml
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<rdf:RDF
 xmlns:aid="http://www.mascem.gecad.isep.ipp.pt/ontologies/aid-em.owl#"
 xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
 xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
 xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
 xmlns:owl="http://www.w3.org/2002/07/owl#"
 xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
 xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
 xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
  <rdf:Description rdf:about="mibel.owl#iSG_821">
    <aid:useTool rdf:resource="aid-em.owl#iBilat"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid20-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid23-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid8-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid19-DayAheadSession2012-01-01-0"/>
    <rdf:type rdf:resource="electricity-markets.owl#Player"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid22-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid15-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid2-DayAheadSession2012-01-01-0"/>
    <aid:useStrategy rdf:resource="aid-em.owl#iStandardPSO"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid3-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid16-DayAheadSession2012-01-01-0"/>
    <aid:useStrategy rdf:resource="aid-em.owl#iSVM"/>
    <aid:useTool rdf:resource="aid-em.owl#iALBidS"/>
    <emo:name>SG 821</emo:name>
    <aid:useStrategy rdf:resource="aid-em.owl#iSimpleRLA"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid13-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid1-DayAheadSession2012-01-01-0"/>
    <aid:useStrategy rdf:resource="aid-em.owl#iTabuSearch"/>
    <aid:useStrategy rdf:resource="aid-em.owl#iGameTheory"/>
    <aid:useStrategy rdf:resource="aid-em.owl#iSimulatedAnnealing"/>
    <aid:useStrategy rdf:resource="aid-em.owl#iANN"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid12-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid7-DayAheadSession2012-01-01-0"/>
    <aid:totalAmountToNegotiate rdf:datatype=
    "http://www.w3.org/2001/XMLSchema#double">34542.3</aid:totalAmountToNegotiate>
    <emo:placesBid rdf:resource="mibel.owl#iBid9-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid14-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid10-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid18-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid24-DayAheadSession2012-01-01-0"/>
    <aid:useStrategy rdf:resource="aid-em.owl#iGA"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid6-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid11-DayAheadSession2012-01-01-0"/>
    <aid:useTool rdf:resource="aid-em.owl#iPortfolioOptimization"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid21-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid4-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid5-DayAheadSession2012-01-01-0"/>
    <emo:placesBid rdf:resource="mibel.owl#iBid17-DayAheadSession2012-01-01-0"/>
  </rdf:Description>
```

Figure 4.32 - SG 821's strategies selection

After receiving the strategies selection and the proposal of player SG 821, the AiD-EM Manager Agent starts the respective agents to run the chosen algorithms in order to achieve the answers with the best prices suggestions for the daily market. Figure 4.33 shows a piece of the answer sent by AiD-EM Manager Agent to SG 821. The full RDF is accessible online[29].

```
1  <?xml version="1.0" encoding="UTF-8" standalone="no"?>
2  <rdf:RDF
3   xmlns:cfp="http://www.mascem.gecad.isep.ipp.pt/ontologies/call-for-proposal.owl#"
4   xmlns:emo="http://www.mascem.gecad.isep.ipp.pt/ontologies/electricity-markets.owl#"
5   xmlns:mibel="http://www.mascem.gecad.isep.ipp.pt/ontologies/mibel.owl#"
6   xmlns:owl="http://www.w3.org/2002/07/owl#"
7   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
8   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
9   xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
10  xml:base="http://www.mascem.gecad.isep.ipp.pt/ontologies/">
11   <rdf:Description rdf:about="mibel.owl#iPrice1-P9-DayAheadSession2012-01-01-0">
12     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">10.0
       </emo:value>
13     <emo:unit>EUR</emo:unit>
14     <rdf:type rdf:resource="electricity-markets.owl#Price"/>
15   </rdf:Description>
16   <rdf:Description rdf:about="mibel.owl#iPeriod20-DayAheadSession2012-01-01-0">
17     <emo:number rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedInt">20
       </emo:number>
18     <emo:id rdf:datatype="http://www.w3.org/2001/XMLSchema#unsignedLong">
       4032629600800994354</emo:id>
19     <rdf:type rdf:resource="electricity-markets.owl#Period"/>
20   </rdf:Description>
21   <rdf:Description rdf:about="mibel.owl#iPower1-P9-DayAheadSession2012-01-01-0">
22     <emo:value rdf:datatype="http://www.w3.org/2001/XMLSchema#double">
       1000.8000000000001</emo:value>
23     <emo:unit>MW</emo:unit>
24     <rdf:type rdf:resource="electricity-markets.owl#Power"/>
25   </rdf:Description>
```

Figure 4.33 - AiD-EM Manager Agent prices suggestion for SG 821

The price suggested for hourly period 9 is the only that can be seen in Figure 4.33 (from line 11 to line 15), with *value* “10.0” and *unit* “EUR”. Henceforth, SG 821 submits its proposal to the market operator considering the prices suggested by AiD-EM’s decision support.

After the market’s execution, the market operator sends the corresponding results to each player. Figure 4.34 exhibits the results achieved by SG 821, when using AiD-EM in the Iberian daily market.

By evaluating Figure 4.34, it is possible to detect that SG 821 failed to sell a bit of its available supply in period 23. The prices offered by SG 821 and the market clearing prices are compared in Table 4.2.

[29] http://www.mascem.gecad.isep.ipp.pt/ontologies/case-study/3/2/#rdf-33

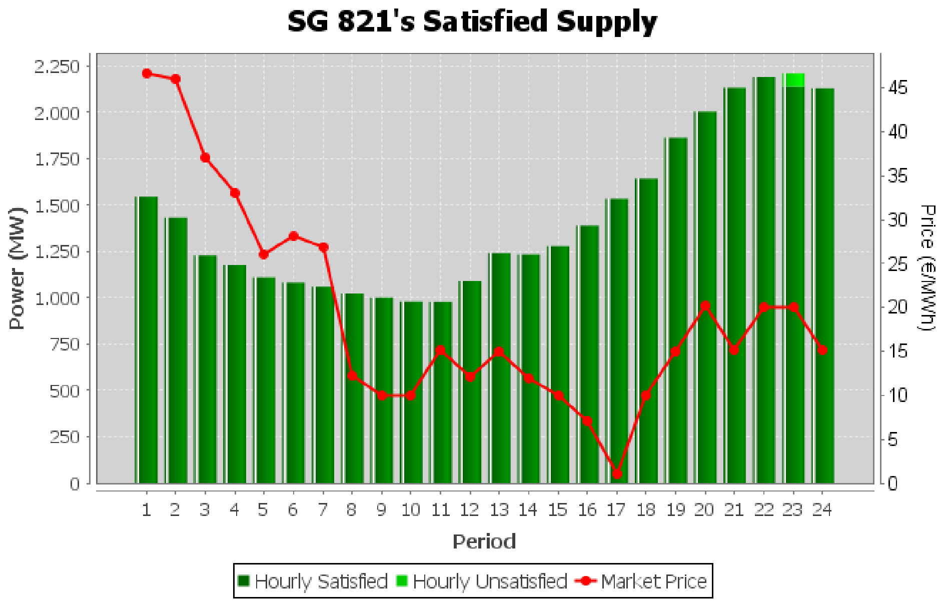


Figure 4.34 - SG 821's results

Table 4.2 - Comparison between prices offered by SG 821 and the market clearing prices

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Offered Price (€)	46	46	36	32	26	28	26	12
Market Price (€)	46,69	46,01	37	33	26,07	28,07	26,89	12,19
Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Offered Price (€)	10	10	15	12	15	12	9	7
Market Price (€)	10	10	15,13	12,13	15	12	10	7,07
Period	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Offered Price (€)	0	9	14	20	15	19	20	15
Market Price (€)	1	10	15	20,13	15,13	20	20	15,13

By analysing Table 4.2 it is perceptible that AiD-EM has proposed bid prices that are very close to the achieved market prices. In some periods the suggested price has even defined the market price. That is the case of hourly periods 9, 10, 13, 14 and 23. However, the demand of period 23 was not enough to ensure the complete sale of this player's supply available for that period.

Although this agent has set the market price in 5 of the 24 periods of negotiation, when comparing the profits achieved before and after the use of AiD-EM's decision support, it is noticed that its profits have reduced slightly, as can be seen by Figure 4.35.

When comparing the profits achieved by SG 821 without the support of AiD-EM, in Figure 4.35 a) with the profits achieved by SG 821 with the support of AiD-EM, in Figure 4.35 b), it can be seen that in a) the profits of the period 23 are slightly higher than those obtained in the period 22, and in turn, in b) the profits of the period 23 are slightly below those achieved in the previous period. This has occurred because the market prices achieved with and without AiD-

EM’s support are essentially the same, and also because this player failed to sell a bit of its supply in period 23. In order to get higher profits this player had to offer higher prices in the periods in which it is the one setting the market price. Even if it could not sell all its available energy, it could achieve a higher profit at the end of the day-ahead market session.

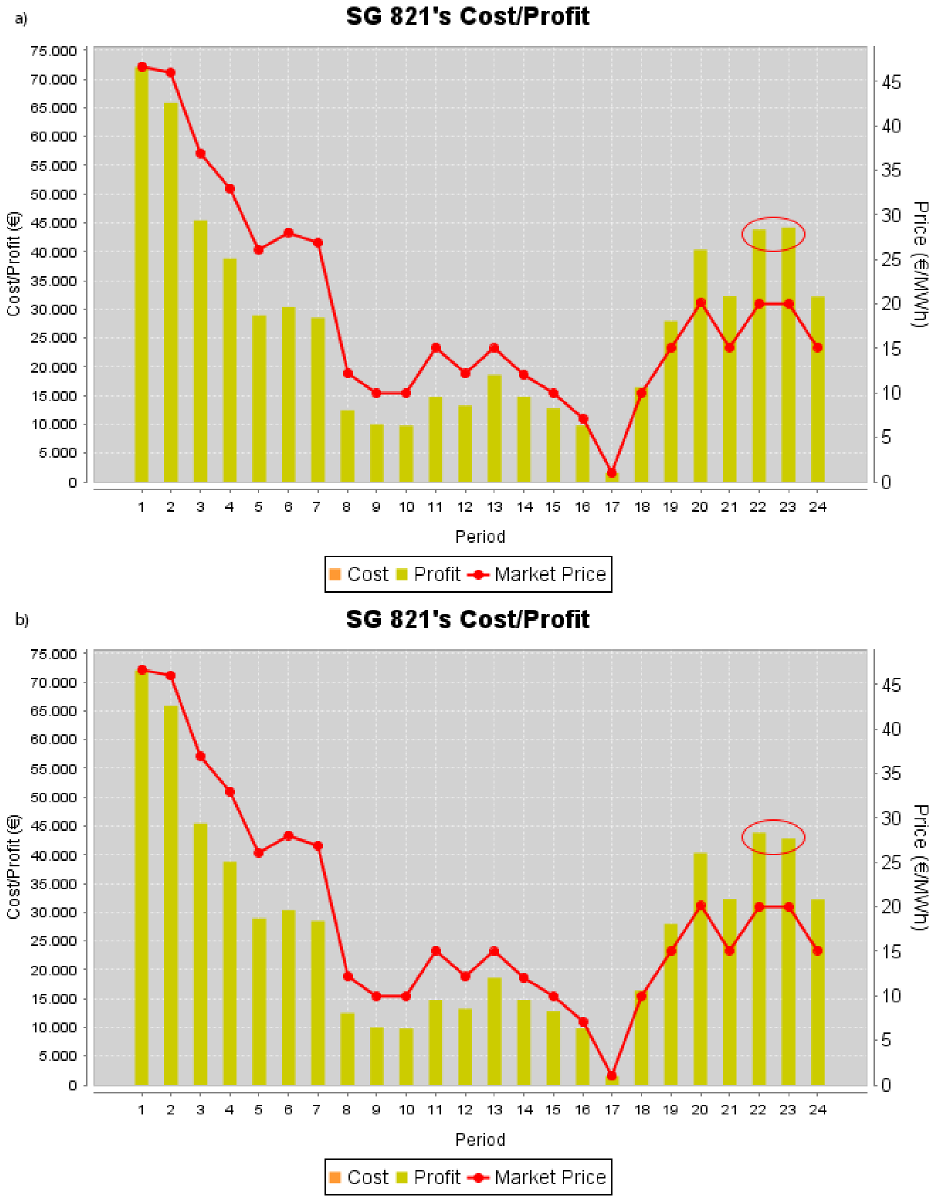


Figure 4.35 - Comparison of SG 821's profits: a) before AiD-EM's decision support; and b) after AiD-EM's decision support.

The publicly available AiD-EM’s ontology allows any player from any electricity market simulator to request for AiD-EM's decision support, taking advantage of its support for market negotiations. In this case, the AiD-EM's ontology granted the player SG 821 – a MASGriP agent participating in MASCEM's Iberian market simulation – with the possibility of requesting decision support for the proposal's prices definition.

As seen from this simulation, the prices suggested by AiD-EM were very close to the clearing price in most of the trading periods, and in some periods the proposed price has defined the market price. Unfortunately, the aid of AiD-EM was not enough to increase this agent's profits, when comparing the results with those achieved in the previous analogous simulation. As discussed in case study 2, AiD-EM is not able to provide advantageous results for the player in market negotiations when considering a single simulation day. AiD-EM's learning process requires several iterations (market executions) in order to provide the necessary data for the training and adaptation of the learning algorithms.

4.5 Final Remarks

The presented case studies demonstrate the advantages of using the proposed and publicly available ontologies for the interoperability between MASCEM, AiD-EM, MASGriP and other multi-agent or single agent systems.

The first case study showed how the use of the proposed ontologies allows players to participate in different market types, including markets that players are not familiar with. Each ontology contains the specific characteristics of each market, granting the inference of market rules from the contained information. Considering these rules, agents' behaviours can be modelled and adapted as illustrated with Seller 22 when converting a MIBEL *Indivisibility* complex condition to an EPEX or Nord Pool block order. On the other hand, in this case study it was also demonstrated the advantage of MASCEM's restructuring. Besides enabling the simultaneous execution of the four simulated scenarios, it also allows the combination of different market models in order to simulate new non-existent EM scenarios.

The interoperability between MASCEM and AiD-EM was demonstrated in the second case study, where Player 56 (from MASCEM), using the AiD-EM's public ontology, decided to request for AiD-EM's decision support for the prices definition in the day-ahead market of MIBEL. As an independent MAS, AiD-EM, using the proposed and publicly available ontologies, enables the interoperability with any agent from any system that may request for decision support in the prices definition, as long as the required decision support is within the scope of the competitive EM.

Finally, in the last case study, the interoperability between MASCEM and MASGriP is demonstrated, as well as the connection between MASGriP and AiD-EM, by using the developed ontologies. The third case study was divided into two scenarios: a) a scenario with a MASGriP agent participating in the Iberian market simulation of the day-ahead and intraday pools; b) in the second scenario, the same player – SG 821 – makes use of AiD-EM's decision support to try to achieve better profits in the simulation of the same day-ahead market pool.

Regardless of the market results for each scenario in the current case studies, they all have proven the usefulness and advantages of using the proposed ontologies for the interoperability between MAS, in the scope of wholesale EM.

5 Conclusions

5.1 Contribution and conclusions

This dissertation presented the conception, development and implementation of ontologies for the interoperability of multi-agent simulation platforms of EM, as well as the deep restructuring of MASCEM - Multi-Agent Simulator of Competitive Electricity Markets.

Considering the constant evolution of EM models and operation, the difficulty for updating old models or including new ones, and the limitations of the old architecture and development platform, it became essential to restructure MASCEM. The main objective of this restructuring was to provide MASCEM with the capabilities to deal with the complex and dynamic EM evolution, besides optimizing its performance.

MASCEM‘s restructuring resulted in an enhanced and FIPA compliant multi-agent simulator, which is able to interact and cooperate with other multi-agent societies through the use of ontologies. Very relevant features, that are essential to the system, have been developed, such as:

- the parallel execution of different simulation scenarios, optimizing the time spent in studying different scenarios;
- the automatic distribution of software agents through the available machines, considering the characteristics of each machine and the resources needed for each agent, thus optimizing the overall system’s performance;
- the easier inclusion, removal or enlargement of market models due to its new modular architecture, which also enables the simulation of hybrid scenarios, accomplishing the future evolution of EM;
- the architectural design, which provides a flexible framework that can be easily extended or integrated with other tools and platforms, increasing the scope of application of MASCEM, and with it, its usefulness for professionals and students of the field;
- the simplification of the agents' model, abstracting the concepts of each entity, avoiding code replication whenever possible;
- a new output format, automatically generated, which facilitates the user analysis, that takes into account the simulated data, including the characteristics and particularities of each type of agent present in the simulation, and from which the result charts are generated;
- the use of configuration files, making it a more flexible tool. Thus avoiding the need to change the code when some base configuration setting needs to be changed, *e.g.* for

database access or access configuration to an external platform, such as AiD-EM or MASGriP;

- the parallelism in accessing data and the implementation of algorithms in the most appropriate programming languages, making MASCEM's execution times much faster than those obtained with the previous architecture;
- the flexibility of execution according to the available time, allowing the user to balance between the results quality and the execution time of the simulations;
- the use of real data, gathered by an automatic extraction tool, enabling the simulation of EM reality.

MASCEM is linked with two other MAS developed within GECAD research group – AiD-EM and MASGriP. Being these systems independent platforms, there is the need to interconnect them in order to enable the study of broader and complex scenarios. Additionally, opening the simulation environment to other systems brings the opportunity of integrating different market models and allows agents, from other systems with very distinct characteristics, to be able to interact in joint simulations. For such, it is mandatory that the messages exchanged by the involved agents may be properly interpreted in all the three MAS. The cooperation between the different platforms can benefit in a large scale the realism and depth of EM and power systems' studies.

There are inherent difficulties in integrating independently developed agent-based systems, especially to access and map private ontologies. To overcome these difficulties, this work disseminates the development of interoperable multi-agent simulators in the EM research area, thus enabling knowledge exchange between them in order to take full advantage of their functionalities, and promoting the adoption of a common semantic that enables the communication between these heterogeneous systems.

To achieve systems interoperability the *Electricity Markets Ontology* has been developed. This ontology contains the main concepts that each specific MAS platform must extend. The proposed ontology facilitates the integration of different MAS, not only GECAD tools, by providing a way for communications to be understood by heterogeneous agents from various systems. By "speaking the same language", agents from different communities can understand each other and communicate efficiently, without the need for spending unnecessary computational resources and execution time (which is an essential issue in a simulation process) in translating messages. In particular for the integration between MASCEM, AiD-EM, and MASGriP, the common concepts are extended from *Electricity Markets Ontology*, avoiding the needs of mapping to interpret messages exchanged between their agents.

The *Electricity Markets Ontology* is the base ontology from which several domain specific ontologies were extended. This is the case of the *MIBEL Ontology*, *EPEX Ontology*, *Nord Pool Ontology*, *Call For Proposal Ontology*, *Electricity Markets Results Ontology* and *AiD-EM Ontology*. The first three ontologies are related with the EM models included in MASCEM. The

Call For Proposal and *Electricity Markets Results* ontologies are common to the three market models, being related with the market proposals definition and results. Finally, the *AiD-EM Ontology* imports *Electricity Markets Ontology* in order to provide decision support to market players from any agent based simulator.

The developed ontologies are public and available online in MASCEM's website[30] so they can be easily accessed, reused and extended by Ontology Engineers or MAS developers in the scope of EM. This is a relevant contribution, not only to provide the participation in joint simulations with GECAD tools, but also to give the basis for the development of other systems specific ontologies.

To support and illustrate the developments achieved during this work, three case studies are presented. They were defined in order to give insights on the relevance of the developed ontologies and the new MASCEM's architecture, and not with the specific aim of illustrating the best results or performance that can be achieved with the new tools.

The use of the developed ontologies enables players to participate in different market types, including markets that players are not familiar with, as has been shown with the first case study. The inference of market rules is granted by the specific characteristics contained in each ontology. Considering these rules, agents' behaviours can be modelled and adapted, as illustrated in the case study while converting a MIBEL *Indivisibility* complex condition to an EPEX or Nord Pool Block Order, and vice versa. The advantage of MASCEM's restructuring has also been demonstrated, by allowing the simultaneous simulation of four scenarios, besides enabling the combination of different market models in order to simulate new EM scenarios.

The second case study has demonstrated the interoperability between MASCEM and AiD-EM, where a MASCEM player requests for AiD-EM's support for bid prices definition. This has been done by using AiD-EM's public ontology. Using the proposed and publicly available *AiD-EM Ontology*, this independent MAS enables the interoperability with any agent from any MAS that may request for decision support in the prices definition within the scope of the competitive EM.

The final and third case study demonstrates the interoperability between MASCEM and MASGriP and between MASGriP and AiD-EM, making use of the developed ontologies. This case study was divided into two scenarios. The first scenario presents a MASGriP's SG player participating in the Iberian market, while the second one illustrates the same player, participating in the same simulation day but, this time, requiring AiD-EM's support for the bid prices definition. Thus, the usefulness and advantage of using the ontologies for the interoperability between the three MAS has been shown.

The new EM simulator resulting from the architectural restructuring of MASCEM and from the integration of the proposed ontologies provides a solid platform to study and explore the

[30] http://www.mascem.gecad.isep.ipp.pt/ontologies

implications and consequences of new and already existing approaches in EM. Researchers of the power systems area consider tools with this type of capabilities essential in order to be prepared to deal with the constant changes in the EM environment. Moreover, market players, operators and regulators can fruitfully take advantage of MASCEM's simulation capabilities to test alternative negotiation strategies trying to maximize their goals.

5.2 Future work

The continuous development of this work is relevant for some on-going international research projects, namely:

- DREAM-GO – Enabling Demand Response for short and real-time Efficient And Market Based smart Grid Operation – An intelligent and real-time simulation approach. This project is coordinated by GECAD and has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement number 641794. It involves US, Spain and Germany;
- SEAS – Smart Energy Aware Systems, project number 12004, under the European Union's EUREKA – ITEA2 program. GECAD participates in all the seven work packages, being responsible for WP4 - Smart Energy Aware Microgrids. It involves Belgium, Finland, France, Romania, Spain and Turkey.

As future work, the inclusion of EUPHEMIA algorithm in MASCEM is previewed, allowing the study and test of new potential alternatives and improvements, which are facilitated by the use of the developed ontologies. EUPHEMIA algorithm has been designed for the market coupling of the European day-ahead markets, while the intraday pools still being managed by each regional market. Thus, besides the EUPHEMIA algorithm, MASCEM should also be complemented with the EPEX and Nord Pool Intraday auction algorithms. The inclusion of GME, the Italian electricity market is also previewed.

A specific module for the development of Java agents by other researchers that wish to test, study or participate in MASCEM's simulations and/or take advantage of the decision support provided by AiD-EM, will also be available in a near future. This module will be available for download on MASCEM's website.

Another important contribution would be the use of the developed ontologies to validate markets' rules, such as the complex conditions, constrained orders (like block orders) or players' submitted bids. The advantage would be to avoid changing the Java code of market algorithms whenever a new rule is introduced or an existing rule is updated or removed. As explained in subsection 2.2.1, auction based markets use the symmetric or asymmetric pools, being the market's rules and constraints validated afterwards. If these validations were made by an ontology inference engine, it would avoid code changes for the execution of the updated algorithms.

The development of ontologies to allow the interoperability between MASGriP and the Aggregators multi-agent simulator is another important issue to be addressed hereafter, enabling external agents the possibility of participating in simulations of both systems. While MASGriP allows the simulation and study of MGs and SGs environments, the Aggregators agent-based system was designed to study the aggregation, and inherent negotiations, of small players allowing their market participation.

Finally, this document intends to contribute to the scientific development of this area, introducing an ontology to promote the power systems and EM simulators interoperability and knowledge sharing between heterogeneous systems. It is publicly available and has been written as simple as possible in order to be properly comprehensive by a wide range of readers, to take advantage of this research and its progress.

References

[Alexopoulos *et al.*, 2009] Alexopoulos P., Kafentzis K., Zoumas C. ELMO: An Interoperability Ontology for the Electricity Market. Proceedings of the International Conference on e-Business, Milan, Italy, July 7-10, 2009.

[Bellifemine *et al.*, 2004] Bellifemine F., Caire G., Greenwood D. Developing Multi-agent Systems with JADE. Wiley Series in Agent Technology, 2004. ISBN: 978-0-470-05747-6 (HB).

[Biggar and Hesamzadeh, 2014] Biggar D. and Hesamzadeh M. (Eds.) The Economics of Electricity Markets. Wiley, 1st edition, September 22, 2014.

[Brost, 1997] Brost W, 1997. Construction of Engineering Ontologies for knowledge Sharing and Reuse. s.l.:s.n.

[Brustolini, 1991] Brustolini J. Autonomous Agents: characterization and requirements. Carnegie Mellon Technical Report CMU-CS-91-204, Pittsburgh, 1991.

[CAISO, 2015] CAISO – California Independent System Operator, homepage: http://www.caiso.com, accessed on September 2015.

[Catterson, 2006] Catterson V., 2006. Engineering Robustness, Flexibility, and Accuracy into a Multi-Agent System for Transformer Condition Monitoring. Doctoral thesis, University of Strathclyde, 2006.

[Catterson *et al.*, 2010] Catterson V. *et al*. An upper ontology for power engineering applications. April 2010. [Online]. Available: http://sites.ieee.org/pes-mas/, accessed on September 2015.

[Cincotti and Gallo, 2013] Cincotti S. and Gallo G. Genoa Artificial Power-Exchange. Agents Artificial Intelligence, 2013.

[Coelho, 1994] Coelho H. Inteligência Artificial em 25 lições. Fundação Calouste Gulbenkian, 1994.

[Cui-Mei, 2009] Cui-Mei B., 2009. Combining Intelligent Agent with the Semantic Web Services for Building An e-Commerce System. In: 2009 IEEE International Conference on e-Business Engineering s.l., IEEE computer society.

[Dai *et al.*, 2013] Dai W., Dubinin V. and Vyatkin V. Automatically Generated Layered Ontological Models for Semantic Analysis of Component-Based Control Systems. IEEE Transactions on Industrial Informatics, vol.9, issue 4, pp. 2124-2136, 2013.

[Dam and Chapping, 2010] Dam K. and Chapping E. Coupling agent-based models of natural gas and electricity markets. In Proceedings of the First International Workshop on Agent Technologies for Energy Systems (ATES 2010), pages 45-52, 11 May 2010.

[Dam and Keirstead, 2010] Dam K. and Keirstead J. Re-use of an ontology for modelling urban energy systems. In Proceedings of the 3rd International Conference on Infrastructure Systems and Services: Next Generation Infrastructure Systems for Eco-Cities (INFRA), Shenzhen, China, 11-13 November 2010.

[Dang and Jennings, 2004] Dang V. and Jennings N. Generating coalition structures with finite bound from the optimal guarantees. Proceedings of the 3rd International Conference on Autonomous Agents and Multi-Agent Systems, pp. 564-571, 2004.

[David and Wen, 2000] David A. and Wen F. Strategic bidding in competitive electricity markets: A literature survey. IEEE Proceedings Power Engineering Society Summer Meeting, 4, 2168-2173, 2000.

[Davis, 1980] Davis R. Report on the Workshop on Distributed Artificial Intelligence. SIGART Newsletter, 1980.

[EAC, 2009] Electricity Advisory Committee, Keeping the Lights On in a New World. January 2009. [Online]. Available: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/adequacy_report_01-09-09.pdf, accessed on September 2015.

[Elamy, 2005] Elamy A. Perspectives in agent-based technology. AgentLink News, 2005, Volume 18, pp. 19-22.

[EMCC, 2015] EMCC – European Market Coupling Company, homepage: http://www.marketcoupling.com/, accessed on April 2015.

[EPEX, 2015] EPEXSPOT - European Power Exchange, Products, Day-Ahead Auction, 2015. [Online]. Available: https://www.epexspot.com/en/product-info/auction, accessed on September 2015.

[Essalmi and Ayed, 2007] Essalmi F. and Ayed L. A Process for the Generation of Personalized Learning Scenarios based on Ontologies. Proceedings of International Conference on Information and Communication Technology and Accessibility, Hammamet, Tunisia, 2007.

[EUPHEMIA, 2015] EUPHEMIA, public description, November, 2013, available: http://www.apxgroup.com/wp-content/uploads/Euphemia-public-description-Nov-20131.pdf, accessed on April 2015.

[Fernandes *et al*., 2013] Fernandes F., Silva M., Faria P., Vale Z., Ramos C. and Morais H. Real-Time Simulation of energy Management in a Domestic Consumer. IEEE PES Innovative Smart Grid Technologies Europe 2013, Copenhagen, Denmark, 06-09 October 2013.

[Fernandes *et al*., 2014] Fernandes R. *et al.* Elspot: Nord Pool Spot Integration in MASCEM Electricity Market Simulator. The PAAMS Collection in Highlights of Practical Applications of Heterogeneous Multi-Agent Systems, Advances in Intelligent Systems and Computing, vol. 430, pp. 262-272, J. Corchado *et al*. Springer International Publishing (Eds), 2014, doi: 10.1007/978-3-319-07767-3_24.

[Ferreira *et al*., 2007] Ferreira M., Vale Z. and Cardoso J. A Congestion Management and Transmission Price Simulator for Competitive Electricity Markets. IEEE Power Engineering Society (PES 2007), General Meeting, Florida 24 to 28 June, 2007.

[Figueiredo *et al.,* 2005] Figueiredo V., Rodrigues F., Vale Z. and Gouveia J. An electric energy consumer characterization framework based on data mining techniques. IEEE Transactions on Power Systems, vol. 20, no. 2, 2005.

[FIPA, 1997] Foundation for Intelligent Physical Agents (FIPA), FIPA Specifications Published in 1997, 1997. [Online]. Available: http://www.fipa.org/repository/fipa97.html, accessed on May 2015.

[FIPA, 2001] Foundation for Intelligent Physical Agents (FIPA), FIPA Ontology Service Specification, 2001. [Online]. Available: http://www.fipa.org/specs/fipa00086/XC00086D.html, accessed on September 2015.

[FIPA, 2002a] Foundation for Intelligent Physical Agents (FIPA), FIPA ACL Message Structure Specification, 2002. [Online]. Available: http://www.fipa.org/specs/fipa00061/SC00061G.html, accessed on April 2015.

[FIPA, 2002b] Foundation for Intelligent Physical Agents (FIPA), FIPA Communicative Act Library Specification, 2002. [Online]. Available: http://www.fipa.org/specs/fipa00037/SC00037J.html, accessed on April 2015.

[FIPA, 2002c] Foundation for Intelligent Physical Agents (FIPA), Standard Status Specifications, 2002. [Online]. Available: http://www.fipa.org/repository/standardspecs.html, accessed on September 2015.

[FIPA, 2003a] Foundation for Intelligent Physical Agents (FIPA), FIPA Standard Repository, 2003. [Online]. Available: http://www.fipa.org/repository/, accessed on April 2015.

[FIPA, 2003b] Foundation for Intelligent Physical Agents (FIPA), FIPA Content Language Specifications, 2003. [Online]. Available: http://fipa.org/repository/cls.php3, accessed on April 2015.

[FIPA, 2004] Foundation for Intelligent Physical Agents (FIPA), FIPA Agent Management Specification, 2004. [Online]. Available: http://fipa.org/specs/fipa00023/, accessed on April 2015.

[FIPA, 2014] Foundation for Intelligent Physical Agents (FIPA), Homepage, 2014. [Online]. Available: http://www.fipa.org/, accessed on April 2015.

[FIPA CCL, 2001] Foundation for Intelligent Physical Agents (FIPA), FIPA CCL Content Language Specification, 2001. [Online]. Available: http://www.fipa.org/specs/fipa00009/, accessed on May 2015.

[FIPA RDF, 2001] Foundation for Intelligent Physical Agents (FIPA), FIPA RDF Content Language Specification, 2001. [Online]. Available: http://www.fipa.org/specs/fipa00011/, accessed on May 2015.

[FIPA SL, 2001] Foundation for Intelligent Physical Agents (FIPA), FIPA SL Content Language Specification, 2001. [Online]. Available: http://www.fipa.org/specs/fipa00008/, accessed on May 2015.

[FIPA-OS, 2003] FIPA-OS, Overview, 2003. [Online]. Available: http://fipa-os.sourceforge.net/index.htm, accessed on May 2015.

[Freeman *et al.*, 2004] Freeman E., Robson E., Bates B. and Sierra K. Head First Design Patterns. O'Reilly Media, 2004.

[Gamma *et al.*, 1994] Gamma E., Helm R., Johnson R. and Vlissides J. Design Patterns: Elements of Reusable Object-Oriented Software. Addison-Wesley Professional, November, 1994.

[GME, 2015] Gestori Mercati Energetici, homepage, 2015. [Online]. Available: http://www.mercatoelettrico.org/En/Default.aspx, accessed on September 2015.

[Gomes *et al.*, 2014a] Gomes L., Faria P., Morais H. and Vale Z. Distributed, Agent-Based Intelligent System for Demand Response Program Simulation in Smart Grids. IEEE Intelligent Systems, 29:56-65, Jan-Feb 2014.

[Gomes *et al.*, 2014b] Gomes L., Fernandes F., Faria P., Silva M., Vale Z. and Ramos C. Real-Time Simulation of Real-Time Pricing Demand Response to Meet Wind Variations. 5th IEEE PES Innovative Smart Grid Technologies Europe (2014 ISGT EU), Istanbul, Turkey, 12-15 October, 2014.

[Gruber, 1993] Gruber T., 1993. A translation approach to portable ontology specifications. In: Knowledge Acquisition. s.l.:s.n., pp. 199-220.

[Gruninger and Lee, 2002] Gruninger M. and Lee J. (2002). Ontology Applications and Design. Communications of the ACM, 45(2), pp. 39–41.

[Harp *et al.*, 2000] Harp S., Brignone S., Wollenberg B. and Samad T. Sepia: A Simulator for Electric Power Industry Agents. IEEE Control Systems Magazine, vol. 20, no. 4, pp. 53 – 69, 2000.

[Hatziargyriou *et al.*, 2014] Hatziargyriou N. *et al*. Microgrids: Architectures and control. Edited by Prof. Nikos Hatziargyriou, IEEE Press, John Wiley and sons, Ltd., 2014.

[Hepp, 2007] Hepp M. Ontologies: State of the Art, Business Potential, and Grand Challenges. In: Martin Hepp, Pieter De Leenheer, Aldo de Moor, York Sure. (Eds.): Ontology Management: Semantic Web, Semantic Web Services, and Business Applications, ISBN 978-0-387-69899-1, Springer, 2007, pp. 3-22.

[Huang *et al.*, 2009] Huang C., Liang W., Lai Y. and Lin Y. 2009. The agent-based negotiation process for B2C e-commerce. Expert Systems with Applications, Volume 37, pp. 348-359.

[Huang *et al.*, 2010] Huang W., Jin J., Jin J. and Wang F. 2010. Technology and Application of Intelligent Agent in Electronic Commerce. In: 2010 International Conference on Measuring Technology and Mechatronics Automation. s.l., IEEE computer society.

[Ivanovic and Budimac, 2012] Ivanovic M, and Budimac Z. Software Agents: State-of-the-Art and Possible Applications. International Conference on Computer Systems and Technologies - CompSysTech'12, June 22-23, 2012, Ruse, Bulgaria.

[JADE, 2015] Java Agent DEvelopment framework, homepage, available: http://jade.tilab.com/, accessed on May 2015.

[Java, 2015] Java programming language – homepage, http://www.java.com, accessed on September 2015.

[Klemperer, 1999] Klemperer P. Auction Theory: A Guide to the Literature. Journal of Economic Surveys, vol. 13, no. 3, pp. 227–286, 1999.

[Koritarov, 2004] Koritarov V. Real-World Market Representation with Agents: Modeling the Electricity Market as a Complex Adaptive System with an Agent-Based Approach. IEEE Power & Energy magazine, pp. 39-46, 2004.

[Li and Tesfatsion, 2009] Li H. and Tesfatsion L. Development of Open Source Software for Power Market Research: The AMES Test Bed. Journal of Energy Markets, vol. 2, no. 2, pp. 111-128, 2009.

[Masolo *et al.*, 2003] Masolo C., Borgo S., Gangemi A., Guarino N. and Oltramari A. (2003). WonderWeb Report. Deliverable D18: Ontology Library. “WonderWeb: Ontology Infrastructure for the Semantic Web” Project, IST Project 2001-33052. [Online] Document available at: http://www.loa.istc.cnr.it/old/Papers/D18.pdf. [Accessed on September 2015].

[McArthur *et al.*, 2006] McArthur S., Davidson E. and Catterson V. Building multi-agent systems for power engineering applications. In Power Engineering Society General Meeting, 2006. IEEE, 2006.

[McArthur *et al.*, 2007] McArthur S. *et al*. Multi-agent systems for power engineering applications - part ii: Technologies, standards, and tools for building multi-agent systems. Power Systems, IEEE Transactions on, 2007.

[Meeus *et al.*, 2005] Meeus, L., Purchala K. and Belmans R. Development of the Internal Electricity Market in Europe. The Electricity Journal, vol. 18, no. 6, pp. 25-35, 2005.

[MISO, 2014] MISO Energy, homepage, http:// www.misoenergy.org, accessed on September 2015.

[Migliavacca, 2007] Migliavacca G. SREMS: a short-medium run electricity market simulator based on game theory and incorporating network constraints. IEEE Power Tech, Lausanne, Swiss, 2007.

[Minsky, 1986] Minsky M. The Society of Mind. Simon & Schuster, Inc. New York, NY, USA, 1986. ISBN: 0-671-60740-5.

[Morais *et al.*, 2012] Morais H., Pinto T., Vale Z. and Praça I. Multilevel Negotiation in Smart Grids for VPP Management of Distributed Resources. IEEE Intelligent Systems magazine, Special Issue "Sustainable Energy and Distributed AI", vol. 27, no. 6, 8-16, November - December, 2012.

[Niles and Pease, 2001] Niles I. and Pease A. Origins of the IEEE Standard Upper Ontology. In Working Notes of the IJCAI-2001 Workshop on the IEEE Standard Upper Ontology, 4-10, 2001.

[Nord Pool, 2015] Nord Pool Spot - Trading, Day-ahead market Elspot, 2015 [Online]. Available: http://www.nordpoolspot.com/TAS/Day-ahead-market-Elspot/, accessed on September 2015.

[Nwana *et al.*, 1999] Nwana H., Ndumu D., Lee L. and Collis J. Zeus: A Toolkit for Building Distributed Multi-Agent Systems. Applied Artificial Intelligence, pp. 129-185, 1999.

[OAA, 2015] Open Agent Architecture (OAA), homepage, available: http://www.ai.sri.com/~oaa/, accessed on May 2015.

[Oliveira *et al.*, 2009] Oliveira P., Pinto T., Morais H., Vale Z. and Praça I. MASCEM – An Electricity Market Simulator providing Coalition Support for Virtual Power Players. International Conference on Intelligent System Application to Power Systems, 2009.

[Oliveira *et al.*, 2012] Oliveira P., Pinto T., Morais H. and Vale Z. MASGriP – A Multi-Agent Smart Grid Simulation Platform. IEEE Power and Energy Society General Meeting 2012, San Diego CA, USA, July 22 - 26, 2012.

[Olsson and Soder, 2008] Olsson M. and Söder L. Modeling Real-Time Balancing Power Market Prices Using Combined SARIMA and Markov Processes. IEEE Transactions on Power Systems, vol. 23, no. 2, 2008.

[OMIE, 2012] OMIE Report, Daily and Intraday Electricity Market Operating Rules, 2012. [Online]. Available: http://www.omel.es/files/reglas_agosto_2012_ingles.pdf, accessed on September 2015.

[OMIE, 2014] OMIE, Resultados de Mercado [in Spanish], 2014. [Online]. Available: http://www.omie.es/aplicaciones/datosftp/datosftp.jsp, accessed on January 2015.

[OMIE, 2015] OMIE, Markets and Products, Electricity Market, About our Market, available: http://www.omie.es/en/home/markets-and-products/about-our-market, accessed on September 2015.

[ONS, 2014] ONS – Operador Nacional do Sistema Elétrico, Electrical System Nacional Operator, homepage: http://www.ons.org.br, accessed on September 2015.

[Panait and Luke, 2005] Panait L. and Luke S. Cooperative Multi-Agent Learning: The State of the Art. Autonomous Agents and Multi-Agent Systems, pp. 387-434, 2005.

[PCR, 2015] PCR report, ITALIAN BORDERS SUCCESSFULLY COUPLED, February, 2015, available: http://www.apxgroup.com/wp-content/uploads/2015-02-24_MRC_PCR_IBWT_Communication_SuccessfulGoLive.pdf, accessed on April, 2015.

[Pereira *et al.*, 2014] Pereira I. *et al.* Data Extraction Tool to Analyse, Transform and Store Real Data from Electricity Markets. 11th International Conference in Distributed Computing and Artificial Intelligence, Advances in Intelligent Systems and Computing, Springer International Publishing, S. Omatu, *et al.* (Eds), 290, 387-395, 2014.

[Pinto *et al*., 2009] Pinto T., Vale Z., Morais H., Praça I. and Ramos C. Multi-Agent Based Electricity Market Simulator with VPP: Conceptual and Implementation Issues. IEEE PES General Meeting, 2009.

[Pinto *et al*., 2011] Pinto T., Morais H., Oliveira P., Vale Z., Praça I. and Ramos C. A new approach for multi-agent coalition formation and management in the scope of electricity markets. Energy, vol. 36, no. 8, pp. 5004-5015, 2011.

[Pinto *et al*., 2013a] Pinto, T., Sousa T., Barreira E., Praça I. and Vale Z. Metalearner based on Dynamic Neural Network for Strategic Bidding in electricity Markets. Second International Workshop on Intelligent Agent Technology, Power Systems and Energy Markets (IATEM 2013) at the 24th International Conference on Database and Expert Systems Applications (DEXA 2013), Prague, Czech Republic, 26-29 August, 2013.

[Pinto *et al*., 2013b] Pinto T., Praça I., Vale Z., Morais H. and Sousa T. Strategic Bidding in Electricity Markets: An agent-based simulator with game theory for scenario analysis. Integrated Computer-Aided Engineering, IOS Press, vol. 20, no. 4, pp. 335-346, September 2013.

[Pinto *et al*., 2014a] Pinto T., Morais H., Vale Z. and Praça I. Multi-Agent Negotiation for Coalition Formation and Management in Electricity Markets. Negotiation and Argumentation in MAS, Bentham Science Publishers Ltd., 2014.

[Pinto *et al*., 2014b] Pinto T., Vale Z., Sousa T., Praça I., Santos G. and Morais H. Adaptive Learning in Agents Behaviour: A Framework for Electricity Markets Simulation. Integrated Computer-Aided Engineering, IOS Press, vol. 21, no. 4, pp. 399-415, September 2014.

[Pinto *et al.*, 2015a] Pinto T., Morais H., Sousa T., Sousa T, Vale Z. and Praça I. Adaptive Portfolio Optimization for Multiple Electricity Markets Participation. IEEE Transactions on Neural Networks and Learning Systems, in press, August, 2015.

[Pinto *et al.*, 2015b] Pinto T., Vale Z. Praça I. Pires E. and Lopes F. Decision Support for Energy Contracts Negotiation with Game Theory and Adaptive Learning. Energies, MDPI, in press, August, 2015.

[Poslad *et al*., 2000] Poslad S., Buckle P. and Hadingham R. The FIPA-OS agent platform: Open Source for Open Standards. 2000.

[Praça *et al.*, 2003] Praça I., Ramos C., Vale Z. and Cordeiro M. MASCEM: A Multi-Agent System that Simulates Competitive Electricity Markets. IEEE Intelligent Systems, vol. 18, No. 6, pp. 54-60, Special Issue on Agents and Markets, 2003.

[Praça *et al.*, 2007] Praça I., Morais H., Cardoso M., Ramos C and Vale Z. Virtual Power Producers Integration Into MASCEM. Establishing The Foundation Of Collaborative Network Book Series IFIP, pp. 291-298, Springer, 2007.

[Rahwan and Jennings, 2008] Rahwan T. and Jennings N. Coalition Structure Generation: Dynamic Programming Meets Anytime Optimization. Proceedings of the 23rd Conference on AI – AAAI, pp. 156-161, 2008.

[Roth and Erev, 1995] Roth A. and Erev I. Learning in extensive form games: Experimental data and simple dynamic models in the intermediate term. Games and Economic Behavior, 8, 164-212, 1995.

[Santos *et al.*, 2011] Santos G., Pinto T., Morais H., Praça I. and Vale Z. Complex Market integration in MASCEM electricity market simulator. International Conference on the European Energy Market 11 – EEM, 2011.

[Santos *et al.*, 2012] Santos G., Pinto T., Vale Z., Morais H. and Praça I. Balancing Market Integration in MASCEM Electricity Market Simulator. IEEE Power and Energy Society General Meeting 2012, San Diego CA, USA, July 22 - 26, 2012, Accession Number: WOS: 000312493707003.

[Santos *et al.*, 2013a] Santos G., Pinto T., Vale Z., Morais H. and Praça I. Upper Ontology for Multi-Agent Energy Systems Applications. Distributed Computing and Artificial Intelligence, 2013, vol. 217, pp. 617-624.

[Santos *et al.*, 2013b] Santos G., Pinto T., Vale Z., Morais H. and Praça I. MASCEM restructuring: Ontologies for scenarios generation in power systems simulators. Power and Energy Society General Meeting (PES), 2013 IEEE, vol., no., pp.1-5, 21-25 July 2013.

[Santos *et al.*, 2015a] Santos G. *et al*. Multi-Agent Simulation of Competitive Electricity Markets: Autonomous systems cooperation for European Market modelling. Energy Conversion and Management, 99, 387-399, July 2015.

[Santos *et al.*, 2015b] Santos G., Fernandes R., Pinto T., Praça I., Vale Z. and Morais H. MASCEM: EPEX SPOT Day-Ahead Market Integration and Simulation. International Conference on Intelligent System Application to Power Systems 2015 - ISAP'15, Porto, Portugal, 11 – 16 September, 2015.

[Schiemann and Schreiber, 2006] Schiemann B. and Schreiber U. (2006). OWL-DL as a FIPA-ACL content language. In Proceedings of the Workshop on Formal Ontology for Communicating Agents, Malaga, Spain.

[Schleiffer, 2005] Schleiffer R. (2005). An intelligent agent model. European Journal of Operational Research, 166(3), pp. 666–693.

[Sioshansi, 2013] Sioshansi F. Evolution of Global Electricity Markets – New paradigms, new challenges, new approaches. Academic Press, 2013.

[SGAM, 2012] SGAM (Smart Grid Architectural Model), report, November 2012. [Online]. Available: http://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf, accessed on September 2015.

[SGETP, 2013] SGETP (Smart Grids European Technology Platform), homepage: http://www.SmartGrids.eu, accessed on October 2015.

[Shahidehpour *et al*., 2002] Shahidehpour M., Yamin H. and Li Z. Market Operations in Electric Power Systems: Forecasting, Scheduling, and Risk Management. Wiley-IEEE Press, pp. 233-274, 2002.

[Sharma *et al.*, 2014] Sharma K., Bhakar R. and Tiwari H. Strategic bidding for wind power producers in electricity markets. Energy Conversion and Management, vol. 86, pp. 259-267, October 2014.

[Sheblé, 1999] Sheblé G. Computational Auction Mechanisms for Restructured Power Industry Operation. Kluwer Academic Publishers, 1999.

[Sousa *et al.*, 2014] Sousa T., Pinto T., Praça I., Vale Z. and Morais H. Reinforcement Learning Based on the Bayesian Theorem for Electricity Markets Decision Support. 11th International Conference in Distributed Computing and Artificial Intelligence, Advances in Intelligent Systems and Computing, Springer International Publishing, S. Omatu, *et al.* (Eds), 290, 141-148, 2014.

[Smith, 2004] Smith B. Ontology. The Blackwell Guide to the Philosophy of Computing and Information. Malden, MA: Blackwell Pub., pp. 155-166, 2004.

[Studer *et al.*, 1998] Studer R., Benjamins V. and Fensel D. 1998. Knowledge engineering: principles and methods. In: Data Knowledge Engineering. s.l.:s.n., pp. 161-197.

[Teixeira *et al.*, 2014] Teixeira B., Silva F., Pinto T., Praça I., Santos G. and Vale Z. Data Mining Approach to support the Generation of Realistic Scenarios for Multi-Agent simulation of Electricity Markets. 2014 IEEE Symposium on Intelligent Agents (IA) at the IEEE SSCI 2014 (IEEE Symposium Series on Computational Intelligence), Orlando, Florida, USA, 09-12 December, 2014.

[Trichakis, 2009] Trichakis P. (2009) Multi Agent Systems for the Active Management of Electrical Distribution Networks. Doctoral thesis, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/57/

[Vale *et al.*, 2008] Vale Z., Morais H., Cardoso M., Ramos C. and Khodr H. Distributed Generation Producers' Reserve Management. IEEE PES General Meeting, 2008.

[Vale *et al.*, 2011a] Vale Z., Pinto T., Praça I. and Morais H. MASCEM - Electricity markets simulation with strategic players. IEEE Intelligent Systems, vol. 26, no. 2, pp. 54-60 Special Issue on AI in Power Systems and Energy Markets, 2011.

[Vale *et al.*, 2011b] Vale Z., Morais H., Pinto T., Praça I. and Ramos C. Electricity Markets Simulation: MASCEM contributions to the challenging reality. Handbook of Networks in Power Systems, Springer-Verlag, 2011.

[Vale *et al.*, 2011c] Vale Z., Pinto T., Morais H., Praça I. and Faria P. VPP's Multi-Level Negotiation in Smart Grids and Competitive Electricity Markets. IEEE PES General Meeting - PES-GM, 2011.

[Veen and Vries, 2008] Veen R. and Vries L. Balancing market design for a decentralized electricity system: Case of the Netherlands. First International Conference on Infrastructure Systems and Services: Building Networks for a Brighter Future, INFRA, 2008.

[Weiss, 2010] Weiss G. Multiagent Systems: a modern approach to distributed artificial intelligence, MIT Press, 2010.

[Wiederhold, 1997] Wiederhold G. Scalable Knowledge Composition. Stanford University, 1997.

[Wooldridge, 2002] Wooldridge M. An Introduction to Multiagent Systems. Wiley, New York, 2002.

[Wooldridge and Jennings, 1995] Wooldridge M. and Jennings N. (1995). Intelligent agents: Theory and practice. Knowledge Engineering Review, volume 10(2): pp. 115–152.

[Wu *et al.*, 2008] Wu J., Guan X., Gao F. and Sun G. Social welfare maximization auction for electricity markets with elastic demand. 7th World Congress on Intelligent Control and Automation, pp. 7157-7162, 25-27 June 2008.

[ZEUS, 2000] The Zeus Agent Building Toolkit, The Zeus Technical Manual, [Online]. Available: http://zeusagent.sourceforge.net/docs/techmanual/part1.html, accessed on May 2015.

[Zimmermann and Thomas, 2004] Zimmermann R. and Thomas R. PowerWeb: a tool for evaluating economic and reliability impacts of electric power market designs. IEEE PES Power Systems Conference and Exposition, vol. 3, pp. 1562-1567, 2004.