A multi-agent approach for planning activities in decentralized electricity markets

E. Gnansounou a, S. Pierre b, A. Quintero b,*, J. Dong a, A. Lahlou a

a Laboratory of Energy Systems (LASEN), Federal Institute of Technology, Lausanne, Switzerland
b Mobile Computing and Networking Research Laboratory (LARIM), Ecole Polytechnique de Montreal, Canada

Received 23 February 2004; accepted 3 June 2006
Available online 19 October 2006

Abstract

Despite the rigour and ability of game theory to cope with oligopolistic electric markets, it fails to model many existing behaviours in the real-world circumstances. The traditional models such as statistical extrapolation or econometrics are not capable to anticipate the changes in the pattern of the market prices due to the future structural changes. Furthermore, in such free and open markets, there is a more intense need for each participant to benefit from a certain level of autonomy, while keeping some capabilities to interact, communicate, collaborate and negotiate with other participants in an efficient way. As a result, there is a need for a novel framework of modelling that could include game theoretical assumptions as well as other more complex assumptions. Agent technologies in general and agent-based simulation in particular offer this possibility. This paper proposes, in a decision-making perspective, a new multi-agent architecture specifically designed to support planning activities in decentralized electricity markets, with a certain level of flexibility. In this model, synthetic agents are created allowing flexible representations of the multi-functional market players and possible mergers and coalitions in the electricity market.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Electricity market; Planning; Multi-agent technology; Power systems; Intelligent decision support system

1. Introduction

The restructing of the Electric supply industry (ESI) has induced the emergence of new actors. More diverse and rich relationships between the market players based on cooperation are developing, shaping new value chains of Electric Power delivery from the generation companies to the consumers. The previous paradigm of electric assets planning based on least cost and central decision process is changing dramatically, prioritising market-oriented decision processes and short-term operations activities. However, planning and anticipation have not disappeared. Investment decisions, portfolios design and management imply medium to longer term forecasting. In the new market environment, the motivation as well as the object of the anticipation is more oriented towards evaluation of the future market prices.

A basic assumption of the Electric Power restructuring is that a fair market has the best ability to give efficient signals to all the players for making decisions that will lead to an optimal social welfare. However, this ideal point of view assumed that the competition is perfect, thus leading to a Pareto optimum. Indeed, in this condition, prices reflect the marginal costs and the allocation of the resources is optimal [2]. Based on this theoretical framework, many authors have advocated that marginal pricing of Electric Power is the most fair and efficient approach independent of the organization form of the electricity market [1,12,20,23,24]. But in the case of competitive market, prices are the outcome of the interactions amongst the market players. Thus, in spot markets for instance, the marginal generation cost does not necessarily reflect the real structure of the generation system, but depends to some extent
on the strategies of the market players. When the market is perfect, the spot price matches the real system marginal cost. However, in case of imperfect markets, strategies of actors prevail.

Traditionally, imperfect market is analysed using game theory and price equilibrium models [4,10,14,18]. The most popular models are Cournot and supply functions equilibria. According to Newbery [21], Bertrand assumptions reflect intense competition when prices are closer to avoidable cost and reserve margin is high whereas less intensive competition should be modelled with Cournot (as in supply functions equilibria). However, other models are presenting in the literature. Berry et al. [3] use the concept of supply function Nash equilibria to model imperfect electricity markets and assert that this game assumption is more reasonable than Cournot–Nash (fixed quantity) or Bertrand–Nash (fixed price, no quantity limit) assumptions.

Despite the rigour and ability of game theory to cope with oligopolistic electric markets, it fails to model many existing behaviours in the real-world circumstances. For example, the short-term maximization of the profit is not always the objective of a company. It could accept in short term to lower price and lose a certain amount in order to consolidate its business by keeping on some big or strategic customers. The traditional models such as statistical extrapolation or econometrics are not capable to anticipate the changes in the pattern of the market prices due to the future structural changes. Furthermore, in such free and open markets, there is a more intense need for each participant to benefit from a certain level of autonomy, while keeping some capabilities to interact, communicate, collaborate and negotiate with other participants in an efficient way. As a result, there is a need for a novel framework of modelling that could include games theoretical assumptions as well as other more complex assumptions. Agent technologies in general and agent-based simulation (ABS) in particular offer this possibility.

In spite of the traditional approaches that model the market price using the resultant behaviour of the whole market players, the ABS estimates the market price as a resultant of many interactions of more or less autonomous players. A few atomistic agents can agglomerate to form one or several synthetic agents (firms) interacting with each other. Each class of atomistic agents could have a specialized function or role (generation, transport, broker, distribution, retail, etc.).

There are some precedent works using agent technologies for modelling and simulating the Electric Power sector [5,15,16,25,26]. However, most of them mainly cope with operation problems and none has presented a generic multi-agent model of competitive electricity market capable to support planning activities. Moreover, the agents are often considered as atomistic agents with one specialized function while, in reality of the electricity market, the agents often play several roles.

This paper proposes, in a decision-making perspective, a new multi-agent architecture specifically designed to support planning activities in decentralized electricity markets, with a certain level of flexibility. In this model, synthetic agents are created allowing flexible representations of the multi-functional market players and possible mergers and coalitions in the electricity market.

Section 2 presents the basic definitions and notation, while Section 3 proposes generic conceptual models for the Electricity supply industry and market. Section 4 presents the multi-agent architecture. Finally, Section 5 concludes by giving the main findings and outlines future research directions.

2. Conceptual models: basic definitions and notation

The Electricity supply industry can be defined as a set of actors and technologies involved in the production, the transport and the distribution of electricity aiming at satisfying the electricity demand of a given community. The main characteristics of the sector are: actors, technologies and transformation of energy. In the context of this paper, each actor is considered as an agent, which can be simply defined as a software module that can achieve specific tasks without direct human supervision in an autonomous way, possibly with a certain level of “intelligence” [8]. In this context, intelligence refers to the capability of reasoning about its environment, inferring new knowledge about the current knowledge stored in its knowledge base, learning from its past experience or from examples and patterns coming from a given expertise domain. Typical agents exist in the literature for retrieving information [11,13,19], for scheduling meetings between many participants [9], for managing urban infrastructures [22].

From a domain standpoint, we can distinguish two kinds of agents to describe the Electricity supply industry: basic agents and synthetic agents. A basic agent is an elementary agent defined by a set of static and dynamic attributes as well as some specific capabilities related to computation, communication and reasoning about its knowledge. A synthetic agent is a combination of some basic agents which act under its control and accordingly to its specific strategies.

2.1. Basic agents

The set of basic agents includes: the consumer (C), the producer or generator (G), the transmission system operator (O), the distributor (D), the market operator (M), the trader/broker or wholesaler (W), the retailer (R), and the regulator (T). The definitions of the agents are specified as follows for the proposed model.

An electricity consumer is an entity that purchases electricity for own use. It may purchase electricity on the spot market and/or the multilateral market through the wholesalers and the retailers. In this model, a basic consumer purchases electricity from the retailers at medium or low voltage.
For a given Electricity supply industry, we can define a list of consumers: \( C = \{ C_i \}, \ i = 1, 2, \ldots, n \). Each consumer \( C_i \) is characterized by a set of static attributes \( CS_{ik}^j, k = 1, 2, \ldots, k_i, \) a set of dynamic attributes \( CD_{it}^j, \ x = 1, 2, \ldots, x_i, t = 1, 2, \ldots, t_i, \) and a set of specific capabilities \( CK_i \). Thus, we can write
\[
C_i = \langle CS_{ik}^j, CD_{it}^j, CK_i \rangle
\]

A producer is an entity that owns one or several power plants and generates electricity for sale. It sells electricity to the spot market and/or the multilateral market through the wholesalers. For a given Electricity supply industry, we can define a list of producers: \( G = \{ G_j \}, j = 1, 2, \ldots, m \). Each producer \( G_j \) is characterized by a set of static attributes \( GS_{jk}^l, k = 1, 2, \ldots, k_j, \) a set of dynamic attributes \( GD_{jt}^l, x = 1, 2, \ldots, x_j, t = 1, 2, \ldots, t_j, \) and a set of specific capabilities \( GK_j \). Thus, we can write
\[
G_j = \langle GS_{jk}^l, GD_{jt}^l, GK_j \rangle
\]

The transmission system operator is an independent body that oversees the non-discriminatory access to the transmission grid, makes dispatching and ensures the quality of service. There is one system operator per transmission system. There may be several system operators in the interconnected transmission systems.

For a given Electricity supply industry, we can define a list of transmission system operators: \( O = \{ O_l \}, l = 1, 2, \ldots, r \). Each operator \( O_l \) is characterized by a set of static attributes \( OS_{le}^l, e = 1, 2, \ldots, e_l, \) a set of dynamic attributes \( OD_{lt}^l, \ \delta = 1, 2, \ldots, \delta_l, t = 1, 2, \ldots, t_l, \) and a set of specific capabilities \( OK_l \). Thus, we can write
\[
O_l = \langle OS_{le}^l, OD_{lt}^l, OK_l \rangle
\]

A distributor is an entity that operates and maintains the distribution system. The function of the distributors is to ensure the security and reliability of the distribution systems.

For a given Electricity supply industry, we can define a list of distributors: \( D = \{ D_k \}, k = 1, 2, \ldots, p \). Each distributor \( D_k \) is characterized by a set of static attributes \( DS_{jk}^l, f = 1, 2, \ldots, f_k, \) a set of dynamic attributes \( DD_{jt}^l, \ \gamma = 1, 2, \ldots, \gamma_k, t = 1, 2, \ldots, t_k, \) and a set of specific capabilities \( DK_k \). Thus, we can write
\[
D_k = \langle DS_{jk}^l, DD_{jt}^l, DK_k \rangle
\]

The role of the market operator is to coordinate the market transactions. His/her functions include: demand forecasting, making call for bid and receiving bids, making economic settlement by the bids merit order and informing the system operator, computing market price, designing market rules.

For a given market, there is one market operator \( M, \) characterised by a set of static attributes \( MS_{bh}^g, h = 1, 2, \ldots, \varphi, \) a set of dynamic attributes \( MD_{bt}^g, \delta = 1, 2, \ldots, \delta_m, t = 1, 2, \ldots, t_m, \) and a set of specific capabilities \( MK \). Thus, we can write
\[
M = \langle MS_{bh}^g, MD_{bt}^g, MK \rangle
\]

A trader/broker or wholesaler is an entity that buys electricity for resale and that does not own generation, transmission and distribution facilities. It buys electricity from the generators and sells electricity to the retailers on spot market and/or multilateral market at high to medium voltage.

For a given Electricity supply industry, we can define a list of wholesalers \( W = \{ W_z \}, z = 1, 2, \ldots, z_w \). Each wholesaler \( W_z \) is characterized by a set of static attributes \( WS_{sz}^v, g = 1, 2, \ldots, g_z, \) a set of dynamic attributes \( WD_{st}^v, x = 1, 2, \ldots, x_z, t = 1, 2, \ldots, t_z, \) and a set of specific capabilities \( WK_z \). Thus, we can write
\[
W_z = \langle WS_{sz}^v, WD_{st}^v, WK_z \rangle
\]

A retailer is an entity that purchases electricity from the traders/brokers at high to medium voltage and resells it to the consumers at medium to low voltage.

For a given Electricity supply industry, we can define a list of retailers \( R = \{ R_q \}, q = 1, 2, \ldots, q_w \). Each retailer \( R_q \) is characterized by a set of static attributes \( RS_{sq}^v, s = 1, 2, \ldots, s_q, \) a set of dynamic attributes \( RD_{st}^v, u = 1, 2, \ldots, u_q, t = 1, 2, \ldots, t_q, \) and a set of specific capabilities \( RK_q \). Thus, we can write
\[
R_q = \langle RS_{sq}^v, RD_{st}^v, RK_q \rangle
\]

The regulator is an administrative agency that imposes the regulation on the market through the laws or other legitimate means. It oversees the market, supervises the behaviours of the market participants, intervenes in rule setting, conflict mediation, etc.

For a given market, there is one regulator \( T, \) characterized by a set of static attributes \( TS_{tr}^v, y = 1, 2, \ldots, y_r, \) a set of dynamic attributes \( TD_{tr}^v, \beta = 1, 2, \ldots, \beta, t = 1, 2, \ldots, t_r, \) and a set of specific capabilities \( TK \). Thus, we can write
\[
T = \langle TS_{tr}^v, TD_{tr}^v, TK \rangle
\]

In this paper, we assume that the sector and the market are formed under specified regulations. However, the regulator agent is responsible for planning of public goods such as the long-term security of electricity supply.

2.2. Synthetic agents

In order to take into account the situations where a participant in a market cumulates more than one basic roles (e.g. an entity that is simultaneously a distributor and a retailer, etc.), we introduce the concept of synthetic agent. A synthetic agent is composed of basic agents and coordinates the actions of its components related to a specified goal and accordingly to some strategies. Nevertheless, these basic agents stay intrinsically autonomous in regard of their specificity and abilities.
The synthetic agents only interact with their component basic agents or with other synthetic agents. Therefore, they do not interact directly with the other basic agents. Association of agents belonging to a same class is a particular synthetic agent that is represented by a singleton.

The set of basic agents is: \( A^b = \{ C, G, O, D, M, W, R, T \} \). Given that the role of a regulator is strictly exclusive, only seven basic agents can be used in the formation of synthetic agents. This set of basic agents is: \( A^b = \{ C, G, O, D, M, W, R \} \).

Thus, the number of possible synthetic agents is: \( 2^{|A^b|} - 1 - |A^b| = 2^7 - 1 - 7 = 120 \).

The synthetic agents defined above are of degree 1 synthetic agents. Degree 2 ones are formed using synthetic agents of degree 1. Finally, hybrid synthetic agents are made up synthetic agents of degree 1 and degree 2.

3. Conceptual models of Electricity supply industry and markets

As far as assets capacity is concerned, the planning process depends on the Electricity supply industry (ESI) structure and particularly on the factors such as: vertical integration/unbundling, concentration/deconcentration, public/private ownership, wide geographical extent/fragmentation, demand elasticity, structure of the electric generating system, reserve margin and regulation. In this section, we present the generic model of Electricity supply industry, the market typology and the conceptual models of the market.

3.1. Conceptual model of Electricity supply industry

Traditionally, the ESI structure was vertically integrated, i.e., for a given consumer, the electrical supply chain from generation to distribution of electricity belongs to the same utility. That is still the case of most of the electricity consumers in the world. The drawback of vertical integration is that all the risks, in particular the risk of over-investment in asset capacities, may be passed to the consumers.

The generic model provides a framework from which specific ESI models could be derived. It is made up basic agents, interactions that are represented by their schemes (see Fig. 1) and their semantic.

3.1.1. Semantic of the generic interactions

In the model framework, the system operator, the market operator, the generators and the wholesalers as basic agents interact at the wholesale level that is at high to medium voltage while the distributors, the retailers and the consumers as basic agents are involved at the retail level at medium to low voltage. The retailers buy electricity from wholesalers. The consumers buy electricity from the retailers.

A synthetic agent \( \{ C, R \} \) is created when a consumer purchases electricity from wholesalers. A synthetic agent of \( \{ C, R, W \} \) is created when a consumer purchases electricity from the generators. In the same way, other multi-functional agents are modelled in this architecture.

3.2. Conceptual model of Electricity market

In this paper, the market model is a sub-model of the ESI conceptual model. It focuses on the electricity transactions and commercial activities in the marketplace. The model includes the agents and the interactions among the agents.

A market is a physical or virtual space (place) in which, according to rules defined for exchanging products or services on agreed temporal horizons, the transactions among the actors are organized. The main elements of the market are: actors, territory, transactions, rules of market, product/service, physical or virtual space (place).

A contract is an agreement between two partners or among several partners in which at least one partner supplies to the others a service at a certain time and/or at a place according to predetermined conditions; in counterpart, it receives a financial or other compensations.

As shown in Fig. 2, two main types of market can be distinguished: organized markets and multilateral markets.

4. The multi-agent architecture

In this section, a multi-agent architecture (MAA) is proposed, specifically devoted to planning issues in the ESI. The aim of this MAA is to build up the skeleton of an intelligent decision support system (IDSS) for selected kinds of problem such us: Security of Electricity supply for an ESI, Expansion of an Electrical Generating, Transmission or Distribution Capacity Systems for a group of decision makers sharing assets, Portfolios of Electricity supply or delivery contracts for a group of actors aggregated by wholesalers or retailers. The main components of this skeleton are the following (Fig. 3): (1) the Problem Formulator and Attributes Evaluator (PROFATE), (2) the Scenarios Builder (SB), (3) the Electricity Market Multi-Agent System (EMMAS), (4) the Decision Making Assistant (DMA).
4.1. The Problem Formulator and Attributes Evaluator

The general structure of the planning problems in the ESI is as follows: a group of entities that may own or operate assets to meet an electricity demand wishes to adapt the capacity and/or the structure of these assets to the evolution of the demand in order to reach a few goals.

This kind of problem can be performed by selecting an appropriate plan amongst a set of alternatives. PROFATE is made up of interfaces and evaluation units (EUs) that assist the user for defining the set of alternatives and their attributes. Depending on the type of planning problem under study and the goals chosen by the user, PROFATE provides a set of alternatives’ attributes concepts and with dedicated interfaces, assists the users to develop consistent scenarios that are stored in a case base.

Using the input given in the PROFATE, a Scenario Evaluator unit interacts with the SB and proposes a scenario to the user who can modify it. The new scenario that will be the active one during the evaluation session is then stored in the cases base.

4.2. The Scenario Builder

The aim of the SB is to develop scenarios to characterize the uncertain environment of the planning activities. Depending on the kind of problem under study, the SB provides a set of scenarios’ attributes concepts and with dedicated interfaces, assists the users to develop consistent scenarios that are stored in a case base.

Using the input given in the PROFATE, a Scenario Evaluator unit interacts with the SB and proposes a scenario to the user who can modify it. The new scenario that will be the active one during the evaluation session is then stored in the cases base.

4.3. The Electricity Market Multi-Agent System

The medium and long-term forecasts of market prices or quantities that are exchanges in the framework of market transactions require the use of simulation models capable to take into account structural changes. The EMMAS is designed in order to perform these simulations. In this paper, the architecture modelling focuses mainly on EMMAS.

The architecture of EMMAS is composed of three essential elements: a group of agents, a set of tasks to be carried out and a set of resources. Each agent in the conceptual market model is represented by an agent in the multi-agent system, and its name is derived from the role it plays in the market. As shown in Fig. 4, the agents are the consumers (C), the producers or generators (G), the transmission system operators (O), the distributors (D), the market operator (M), the traders/brokers or wholesalers (W), the retailers (R), the regulator (T), the synthetic agents (AS) and the book-keeper. Each participant is autonomous and should be responsible for own decision making.

Communication and cooperation are two most important capabilities of the multi-agent systems. The term cooperation is assumed to include both collaboration and competition [22]. In EMMAS, the agents are designed to have the capability to collaborate or compete. Collaboration is the base of the synthetic agents, and competition is the base of the electricity market.

One of the features of EMMAS is the ability to model actual electricity entities of the ESI. For example, Electricity Generation company may be: (1) an independent power...
producer (IPP) which activities only focus on generation in a given area; (2) an IPP with its resources split into several geographic areas governed each by an entity with a certain level of autonomy; (3) a generation component of a vertically integrated utility. Even all these kinds of generator share similar requirements, their degree of autonomy may vary significantly. EMMAS provide classes of agents that can be instantiated to model each of them (Fig. 5).

For example the class \{C, R, W, G\} represents a kind of enduser that includes retail, wholesale and generation entity and whose goal is mainly to meet its own electricity demand. Degree 2 enduser is a kind of enduser that includes sets of degree 1 endusers that may be bound by alliance relationships, i.e., union of sets of consumers located in different geographic areas but purchasing electricity from the same wholesaler whose asset is shared amongst them. Hybrid enduser is a set made up of basic endusers and degree 1 ones.

Once a class of agent is instantiated, its knowledge about the electricity market is organized in its knowledge base. As the trading process progresses, this knowledge base changes and is enriched with new knowledge obtained from other agents and from its own reasoning. For example, Fig. 6 shows the knowledge representation of the generator agent.

The communication language KQML [6,7] is used to represent the knowledge or the content of the message itself. Fig. 7 shows an example of coordination dialogue between consumers, market operator and generators in the case of spot market. The spot markets are managed by a market operator. All the transactions in those markets must lead to physical delivery. The auction can be simple, each consumer indicates the day before its requirements in terms of quantities. The demand is forecasted by the market operator to the producers. Then, each producer indicates the day before its offers in terms of prices and quantities for the different rounds of the following day. The offers are then classified according to their prices and are used to build a production curve indicating the best schedule (least cost) to meet the demand.

The autonomy of an agent that is a component of a synthetic agent is bound through the control function that is made up of the specification of its goals, its plans, and its strategies. Once a hierarchical agent has defined the control function of a component agent, the latter has autonomy in the implementation phase.

As it is the case in PROFATE, the capabilities of agents are modelled through EUs that are specialized each in kinds of task such as: forecast of market clearing prices based on the stored historical information and on the competitiveness of the agent’s consortium; forecast of the load flow in the transmission or distribution wires. These tasks
are undertaken for a given scenario provided by PROFATE. Some results of simulations undertaken by EMMAS’s EUs may complement scenario’s attributes in SB.

4.4. The Decision Making Assistant

The DMA plays two roles within the MAA. First, it is a global coordinator between PROFATE, SB and EMMAS. Second, it aims at performing the comparison of the alternatives defined in PROFATE under various scenarios and associate actors. For this latter task, a method of Group decision support based on ELECTRE III is used in DMA [17].

4.5. Illustrative example

In order to illustrate how the EMMAS works, we present a simplified example related to the evaluation of generation investment in a competitive environment. As the outline of the general approach adopted, the project evaluation includes the multi-agent simulation of electricity market and the economic appraisal. The main output is the spot price that provides the investors with the market signals. If the price is high, the existing generator agents may expand the capacity and the new investors will enter the market. The new power plant is evaluated on the basis of the market information and the estimations on the fuel prices, the investment cost, etc. With the new entrances, the market price will be falling down until an equilibrium level – the long-term marginal cost of electricity production.

4.5.1. The agent environment

The electricity market actors’ environment is a complex one. The electrical network model takes into account the power plants, the high tension transport lines, the distribution sub-stations and different types of contracts, among other things. Several elements of the model that required specific processing have been converted into Java classes while others, more static elements, have been stored in the environment’s database.
4.5.2. Knowledge base

Some of the pertaining elements of the environment as well as information on the actors have been stored in a MySQL database. The database’s relational model is illustrated in Figs. 8–10.

The power plants (PowerPlant) are of some specific type (nuclear, hydrothermic, etc.) and are the property of a producer (Generator). Each power plant keeps a trace of the last offer it received for each round and is composed of zero, one or many units of production (see Fig. 8 for details).

The electricity transport system (see Fig. 9 for details) has a quality of service property and is composed of several high tension lines (line). A line is managed by a company and links a sub-station (using class A high tension lines or low tension lines) or a power plant (using very high tension lines) to a destination sub-station.

A sub-station is located in a subzone within a designated zone and is the property of an electricity distribution company.

A contract pertains to one or many products or services and is signed by at least two agents (see Fig. 10 for details).

4.5.3. The application

The case illustrated here is one where simple biddings are negotiated on a market for delivery on the following day. The only actors that are considered in this particular case are the wholesaler (W), the market operator (M) and the electricity producers (G). The wholesaler has either already received and aggregated all client demands or made an estimation of those demands.

The number of wholesalers is I > 1 and the demands are stated as time periods and cover an entire 24-h day from the time the biddings start.

The considered scenario take h = 1 and corresponds to day D + 1, 5 h, and h = 24 to day D + 2, 4 h. There is a single market operator per market. He sums all demands that were made on the market for each time period. Each producer knows the quantity of electricity that each of his power plants can offer and tries to fulfill all invitations to tender according to a particular strategy.

The market operator classifies all tenders by increasing price order until all demands in a time period have been fulfilled. The price of the last accepted offer will be considered as the system’s marginal price (SMP).

The operational aspects of the market are shown in Table 1. In the following, we will detail the operational processes used by the market operator and the producers.

(1) Role of the market operator

We will illustrate the market operator’s role using a simple example. If we take a simple time period where there is a 500MWh demand and a set of offers (quantity, price) as shown in Table 2, line B1. Table 2 classifies all offers by increasing price order while Table 3 shows the offers that were finally accepted.

Case 2 takes into account a certain loss probability by adding a 25% cushion to the demand. Indeed, at the end of the presented process, only 125 of the 200KWh offered will be selected from the producer (G) that made the last offer (200, 4.5). In the studied system, none of the producers are forced to accept such an update on their offer. This problem or crisis will be solved between 14:00 and 15:59 by applying the following rules:

Fig. 8. Production market model.
Fig. 9. Transport and distribution market model.

Fig. 10. Contracts, products and services model.
1st Case: the producer \((G)\) accepts the update on the quantity it initially offered without modifying the original price. There is no need for further negotiation.

2nd Case: the producer \((G)\) refuses the update on its offer. In that case, the market operator \((M)\) assigns to the problematic offer the “Special Bid” and publishes a new invitation to tender for the remaining quantity required to satisfy the initial demand, 125 in this case. The goal here is to find an alternative solution to the problematic offer without exceeding the initial demand. The new invitation to tender will hence limit itself to optional offers whose quantity will be close to the problematic offer and that will

| Table 1 | Chronological decisions and communications within the implemented electricity market model |
| --- | --- | --- |
| Jour \((J - 1, J + 1, J + 2)\) | Heure (h:m) ou (h1–h2) | Action \(i\) |
| \(J - 1\) | 9:00 | Each wholesaler \((W)\) must anticipate the demand for each time period of day \(D + 1\) at 5 h until \(D + 2\) at 4 h. |
| \(J - 1\) | 10:00 | Each wholesaler \((W)\) must send its demand forecasts to the market operator \((M)\). |
| \(J - 1\) | 10:01–13:59 | The market operator \((M)\) processes all demands received from wholesalers by verifying: 1 – each wholesaler’s solvability. 2 – aggregating demands by time periods. |
| \(J - 1\) and \(J\) | 14:00 | The market operator \((M)\) publishes the invitations to tender that must be fulfilled. |
| \(J - 1\) and \(J\) | 14:01–9:59 | The producers \((G)\) process the tenders following the scheme detailed in Table 2. These tables are filled using the producer’s strategy (see Section 4.3 for details). The offers are sent to the market operator \((M)\). |
| \(J\) | 9:59 | The end of the period where producers \((G)\) can make offers. |
| \(J\) | 10:00 | The market operator \((M)\) ends the offer period. |
| \(J\) and \(J\) | 10:01–14:00 | The market operator \((M)\) selects the offers following a given selection procedure (see Section 4.2 for details). |
| \(J\) and \(J\) | 14:01–15:59 | The market operator \((M)\) negotiates with all producers \((G)\) in the market and determines the system’s marginal price. |
| \(J\) | 16:00 | The market operator \((M)\) publishes the results of the invitations to tenders. |

| Table 2 | Ordering of the offers |
| --- | --- | --- |
| B1 | B2 | Combined quantity | B3 |
| (100,3) | (100,2) | 100 | |
| (100,2) | (100,3) | 200 | |
| (300,4) | (300,4) | 500 | |
| (200,4,5) | (200,4,5) | 700 | |
| (150,5) | (150,5) | 850 | |

| Table 3 | Offers that were retained |
| --- | --- | --- |
| Case 1: Demand to satisfy \(= 500\) |
| B1 | B2 | Combined quantity | B3 |
| (100,3) | (100,2) | 100 | (100,2) |
| (100,2) | (100,3) | 100 | (100,3) |
| (300,4) | (300,4) | 500 | (300,4) |
| (200,4,5) | (200,4,5) | 700 | |
| (150,5) | (150,5) | 850 | |

| Case 2: Demand to satisfy \(= 625\) (added a 25% cushion) |
| --- | --- | --- |
| B1 | B2 | Combined quantity | B3 |
| (100,3) | (100,2) | 100 | (100,2) |
| (100,2) | (100,3) | 100 | (100,3) |
| (300,4) | (300,4) | 300 | (300,4) |
| (200,4,5) | (200,4,5) | 700 | (200,4,5) |
| (150,5) | (150,5) | 850 | |
propose a quantity at least equal to the quantity required to fulfill the demand for that particular time period. In our particular case, the optional offer’s price is 5 for the amount of electricity demanded. In terms of costs and to minimize the SMP, the market operator \((M)\) will most likely accept the initial offer that was labeled “Special Bid” at \((200, 4.5)\).

3rd Case: the producer \((G)\) accepts to review the quantity offered. The quantity is then reduced to the demand of the market operator \((M)\) but the price is updated within a specified limit and according to the quantity required by the market operator \((M)\). As in the second case, the market operator will label this offer as a “Special Bid” and will try to find a better offer through the publication of a new invitation to tender on the market. The difference between this case and the previous case is that if the market operator \((M)\) deems the updated offer reasonable, he will not proceed further and will simply retain the updated offer. Moreover, at the end of an eventual negotiation period, the most interesting offer will be selected.

\((2)\) Producer’s strategy (Min-max Regret Criterion)
The goal of the producer \((G)\) is to maximize its profits under the following assumptions:

- A1: Within the power plant portfolio of a producer \((G)\), the price of the offer must follow the order of the marginal costs of the power plants.
- A2: The quantity offered by a power plant corresponds to the quantity the plant can generate at full regime \((100\%)\).
- A3: The power plants never offer electricity at a cost lower than their marginal costs.
- A4: Each producer forecasts its hourly SMP.
- A5: The price of the starting offer \((\text{Day 0})\) is equivalent to the marginal cost of the power plant.

Global Algorithm

- Selection of a power plant whose marginal cost is in the neighborhood of the considered SMP. One power plant by producer \((G)\) is chosen. The power plant that has highest marginal cost but at the same time that is in the neighborhood of the SMP. All other power plants maintain Statu Quo on their offers and will be the starting point of all the states of the market derived from this point on.
- Construction of the state of the market: since every power plant can take three actions, there are \(3^{p-1}\) possible states the market can be in for \(p\) power plants (including the one associated with the considered producer \((G)\)). Different constraints such as the minimal price, the maximal price and the marginal cost limit the action a power plant can take.
- Computing the usefulness of each cell: for each possible state of the market, the utility of each cell is essentially the profit that a producer \((G)\) can make according to the recomputed SMP and the offers from that producer \((G)\) that have been retained.
- Once the base matrix is filled, the Savage algorithm with the Min-max Regret Criterion is applied to determine the best possible action that the producer can take.

Min-max Regret Criterion: Given a matrix \(M\) where each cell \(M_{ij}\) is an action \(A_i\) in a state of the market \(S_j\), the goal is to find the least unfortunate action in the worst possible case.

\(4.6.\) Results

We will now present the results visualization tool: SMP-Graph. The goal of this tool is to offer real-time visualiza-
tion capabilities on the evolution of the market to be able to adjust market parameters.

Figs. 11 and 12, respectively, show simulation days 11 and 52. Note that the coordinate axes have been re-dimensioned according to minimum and maximum values that have been found during the simulation. The curves of each time period can be displayed by checking the associated box.

5. Conclusion

With the restructuring of the Electric supply industry (ESI), a new paradigm has emerged in planning of the electric assets. The role of the market is growing up. However, that does not preclude the anticipation of the investment. In this paper, a multi-agent architecture is proposed as a platform for market-oriented activities in ESI. Based on this architecture, an Intelligent Decision Support System (IDSS) is being developed. The skeleton of this IDSS includes four main components: Problem Formulator and Attributes Evaluator, Scenario Builder, Electricity Market Multi-agent System and Decision Making Assistant. One application example is given as illustration to prove the wealth of the proposed models. Future research work will consist of using the architecture for modelling real and complex cases and then expand it in order to include operation issues.

Acknowledgement

The authors thank Denis Bedniaguine from LASEN for its helpful comments during the discussions leading to this paper.

References