TOWARD A MULTI-AGENT ARCHITECTURE FOR MARKET ORIENTED PLANNING IN ELECTRICITY SUPPLY INDUSTRY

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

Abstract

The liberalization of the electricity supply industry has shifted the analyses and modelling activities from planning to operation. However, project studies and investment appraisal still require medium and long-term anticipation of the electricity market prices. The models traditionally used for making such projections i.e. statistical extrapolation or econometrics fail to capture the future structural changes in the emerging electricity markets. There is a need for a novel framework of modelling that could extend game theoretical assumptions to more complex ones. This paper proposes, in a decision-making perspective, a new multi-agent architecture specifically designed to support flexible planning activities in decentralized electricity markets. In this model, the concept of synthetic agents is used for modelling in flexible forms multi-functional market players, possible mergers and coalitions in the electricity market.

Key Words

Electricity market, planning, multi-agent technology, synthetic agents, power systems, intelligent decision support system

1. Introduction

The ongoing restructuring of the electric supply industry (ESI) has induced several changes in the types and function of the actors as well as in the relationships between the market players. More diverse and rich interactions are developing, shaping new value chains of electric power delivery. The paradigm of electric assets planning based on least cost and central decision process [1] is changing dramatically to market-oriented decision processes and short-term operations activities. However, investment decisions, portfolios design and management require medium to longer term forecasting. In the new paradigm, the anticipation of the market prices plays a dominant role in planning activities.

While the electric power restructuring is expected to provide efficient signals to all the players and achieve an optimal social welfare, the real world cases do not confirm that expectation. The ideal point of view assumes that the competition is perfect, thus leads to a Pareto optimum [2]. This theoretical framework is put forward by many authors who advocate that marginal pricing of electric power is the most fair and efficient approach whatever organization pattern the electricity market depicts [3–7]. Their motivation is to serve economic efficiency goals. However, in the case of competitive market, prices are the outcome of the interactions amongst the market players and reflect the imperfections of the market. In spot markets for instance, the marginal generation cost does not necessarily reflect the real structure of the generation system, but it may emerge from the strategies of the market players, especially when the market is imperfect.

Game theory is the traditional tool used to cope with imperfect markets [8–11]. In that frame, Cournot and supply-functions equilibria are the most popular models. However, other strategic interactions have been surveyed in the literature [12] as being relevant for the electric power markets; they include the following behaviours: game in prices (generalized Bertrand strategy), collusion, leader-follower games (Strackelberg) and the generalized conjectural variations.

Ventosa *et al.* [13] present simulation models as an alternative to equilibrium models for coping with complexity of real problems. Those models represent the behaviour of actors as sequential rules. One of the complexity sources of electric power markets modelling stems from the possible structural changes in the future. Mergers, acquisitions, strategic alliances are impacting significantly the pattern of the prices evolution making projection more challenging than in the tradition electricity market.

Agent technologies in general and agent-based simulation (ABS) in particular offer the possibility to represent

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each market player as an agent that benefits from a certain level of autonomy, while keeping some capabilities to communicate, collaborate and negotiate with other players in an efficient way. The ABS estimates the market price as a resultant of many interactions of more or less autonomous players.

Several precedent works used agent technologies for modelling interactions between electric market players [14–18]. The “electricity market complex adaptive system” (EMCAS) [19] and the “simulator for electric power industry agents” (SEPIA) [20] are two examples of tool for electricity markets analyses based on agent technologies. However most of those tools mainly cope with operation problems and none has presented a generic multi-agent model capable to support planning activities in electric power markets. Moreover, the agents are often considered as atomistic agents with one specialized function i.e. generation, transmission, wholesale, distribution, retail, whereas in the real world electricity market, the agents often play several roles.

In this paper, a multi-agent architecture designed to support planning activities in decentralized electricity markets is applied to appraise investment of a new power plant in a competitive market.

After presenting in Section 2 the conceptual models for the electricity supply industry and market, the main characteristics of the multi-agent architecture are analyzed in Section 3. In Section 4 the proposed architecture is illustrated with an example of investment appraisal. Finally, Section 5 gives the main findings and outlines of future research directions.

2. Conceptual Models

2.1 Concept of Agent

The ESI is defined as a set of actors and technologies involved in activities of generation, transmission and distribution and trading of electricity aiming at satisfying the electricity demand of a given community. In the context of this paper, each actor is considered as an agent, which can be defined as a software module designed to achieve specific tasks in an autonomous way, possibly with a certain level of “intelligence” [21] including 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 [22–24], for scheduling meetings between many participants [25], for managing urban infrastructures [26].

In the proposed architecture two kinds of agents are used to describe the ESI: 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. These concepts were defined in detail in Gnansounou *et al.* [27]. They are briefly recalled in this section for completeness purpose.

2.2 Basic Agents and Synthetic Agents

The basic agents are used to model entities related to elementary functions such as: the Consumer (C), the Producer or Generator (G), the Transmission Networks Company (N), the Distributor (D), the Market Operator (M), the Trader/Broker or Wholesaler (W), the Retailer (R), and the Regulator (T). Each basic agent has well-defined roles and is characterized by a set of static attributes, a set of dynamic attributes and a set of capabilities. Table 1 gives the main roles of the basic agents.

We introduce the concept of *synthetic agent* to model the companies that cumulate more than one basic role (e.g., an entity that is simultaneously a distributor and a retailer, etc.), A synthetic agent is composed of agents and coordinates the actions of its components related to a specified goal and accordingly to some strategies. The component agents stay intrinsically autonomous in regard of their specificity and abilities.

Regarding the complexity of the Agent, five types of synthetic agents are used in the proposed architecture: degree 0 synthetic agents defined above are the basic agents; synthetic agents of degree 1 are made of basic agents; degree 2 ones are formed using synthetic agents of degree 1. Finally, hybrid agents of degree 1 are made up degree 1 and degree 0 synthetic agents whereas degree 2 hybrid agents are associations of degree 2 synthetic agents and a lower degree synthetic agent (degree 1 or 0 synthetic agent).

For example, the Regional Transmission Organization (O) is modelled by a degree 1 synthetic composed of Transmission Networks Companies (Ns). There is only one (O) for each transmission system. Its responsibility includes: lead, coordinate or perform the operation, insure the security and reliability of the regional transmission, assure a non discriminatory access to the transmission for all the market participants, in particular, set a region-wide tariff that avoids rate “pancaking”, and coordinate the planning/investment for the expansion of the transmission system. It can be shown that the proposed generic model of the transmission involving Transmission Networks Companies (Ns) and the Regional Transmission Organization (O) can be adapted to any real model i.e., Independent System Operator (ISO), Independent Scheduling Administrator (ISA), Independent Transmission Company (ITC or TransCo). In presence of inter-regional system, we model the Trans-Boarding Transmission Organization (B) using a degree 2 synthetic agent composed of (Os). A Regional Transmission Organization (O) that is also responsible of the operation of a regional market (M) is modelled by a degree 1 hybrid agent {O, M}. In presence of a large trans-boarding market, we model a Trans-Boarding Transmission Organization (B) that is also responsible of the operation of the market by a degree 2 hybrid agent {B, M}.

Table 1
Main Roles of the Basic Agents in the Proposed ESI Model

Basic Agents	Main Roles
Consumer	Purchases electricity for own use; may purchase on the spot market and/or multilateral market through the retailers at medium to low voltage.
Generator	Owns or leases under long-term contracts one or several power plants, operates them and sells electricity to the spot market and/or the multilateral market through wholesalers.
Transmission networks company	Owns or leases under long-term contracts one or several transmission networks and may operate its facilities under the coordination and the direction of the regional transmission organization (RTO).
Distributor	Owns or leases under long term-contracts a distribution grid, operates it, and ensures the security and reliability of the distribution system.
Market operator	Coordinates the market transactions; his/her functions include: demand forecasting, making calls for bids and receiving bids, making economic settlement by bids merit order and informing the RTO, and computing market prices.
Wholesaler	Buys electricity from generators for reselling to the retailers on spot and/or multilateral markets at high to medium voltage; does not own generation, transmission, or distribution facilities.
Retailer	Purchases electricity from the wholesalers at high to medium voltage and resells it to the consumers at medium to low voltage; does not own generation, transmission, or distribution facilities.
Regulator	Administrative agency; designs and controls the regulation on the market through laws or other legitimate means. It oversees the market, supervises the behaviours of the market participants, intervenes in rule setting, conflict mediating, and market mechanisms complementing in cases of failure of market. 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.

2.3 Electricity Supply Industry (ESI)

A generic model of the ESI is proposed made up basic agents, the generic interactions among them (see Fig. 1) and their semantic.

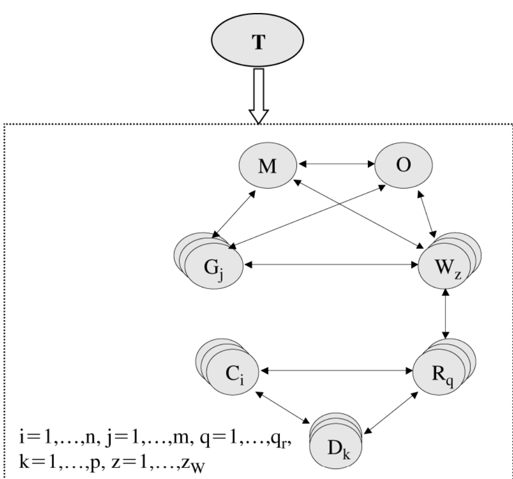

Figure 1. ESI generic interactions.

All entity and organization within the ESI is supposed to be modelled from that basic model, using the concept of synthetic agent. For example, the case of consumer purchasing electricity from generators is represented using a synthetic agent of {C, R, W} and the subset of interactions among the component agents. The semantic of these interactions is then adapted accordingly.

As electricity market is an organization within the ESI, its model derives from that of the ESI. It focuses on the electricity transactions and commercial activities on the marketplace. The model includes the agents and their interactions.

The main aspects and components 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.

Two main types of market can be distinguished: organized markets and multilateral markets (see Fig. 2).

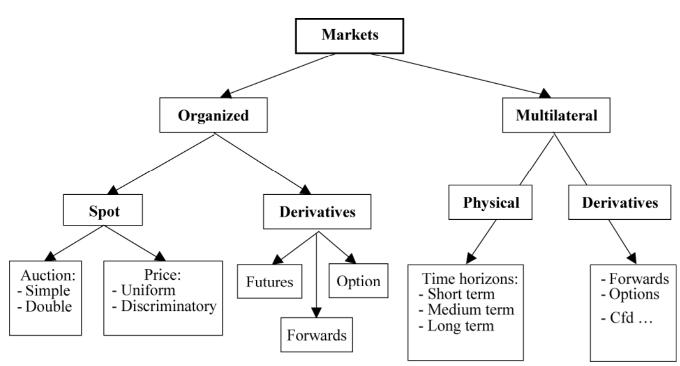

Figure 2. Market typology.

3. The Multi-Agent Architecture

3.1 The Structure of the Intelligent Decision Support System

The proposed multi-agent architecture (MAA) is composed of the following modules (see 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). The aim of the 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.

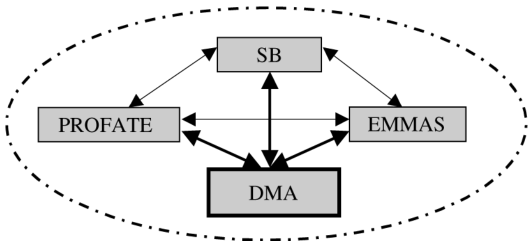

Figure 3. Outline of the IDSS structure.

The different modules have been presented in detail by the authors in a previous paper [27]. In this paper we focus on the MAAS module.

3.2 The Electricity Market Multi-Agent System (EMMAS)

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 MAA 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 (Fig. 4). 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. 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).

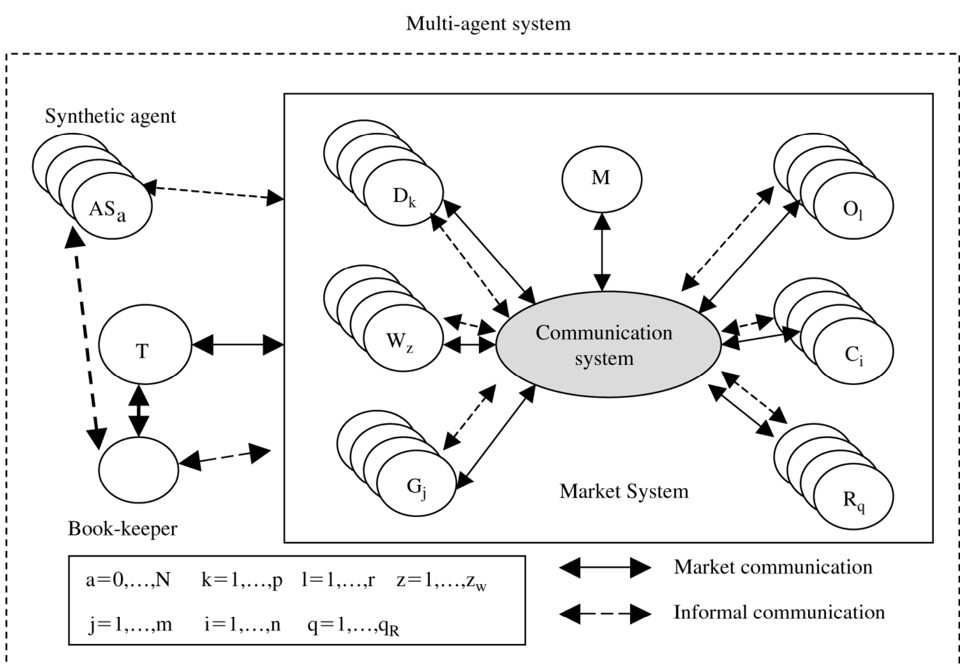

Figure 4. Multi-agent architecture for market-oriented planning in electricity supply industry.

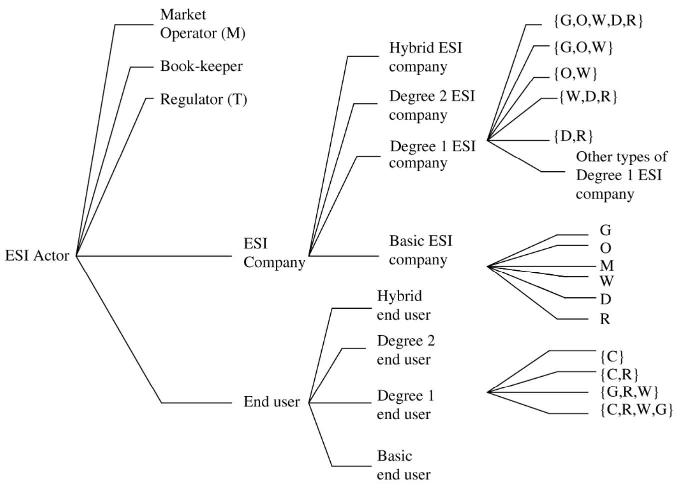

Figure 5. Taxonomic hierarchy of agent classes used in EMMAS.

For example the class {C, R, W, G} represents a kind of end-user that includes retail, wholesale and generation entity and whose goal is mainly to meet its own electricity demand. Degree 2 synthetic end-user is a kind of end-user that includes sets of degree 1 synthetic end-users 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 end-user is a set made up of basic end-users 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.

```
Name : < string >
Address : < string >
Account number : < number >
Identity number : < number >
Number of plants : < number >
List of traders/brokers : < W1, W2, …, Wz >
Market operators : < M >
List of transmission system operators : < O1, O2, …, Ol >
List of plants : <
        < plant 1 :
            < Type of the power plant : {renewable energy,
                                         non-renewable energy } >
            < Capacity : MW >
            < Maximum output of generating unit : MW >
            < Minimum output of generating unit : MW >
            < Unit forced outage rate : % >
            < Heat rate of generation unit : GJ/MWh >
            < Annual fixed operation cost : $/KW, year >
            …
        >
        …
        < plant k :
            < Type of the power plant : {renewable energy,
                                         non-renewable energy } >
            < Capacity : MW >
            < Maximum output of generating unit : MW >
            < Minimum output of generating unit : MW >
            < Unit forced outage rate : % >
            < Heat rate of generation unit : GJ/MWh >
            < Annual fixed operation cost : $/KW, year >
            …
        >
    >
```

Figure 6. Knowledge representation: Generator agent.

The communication language KQML [26, 28] is used to represent the knowledge or the content of the message itself. Fig. 6 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.

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. Evaluation of an Electric Power Generating Plant using EMMAS

4.1 The Context

In order to illustrate how the module EMMAS works we present a simplified example related to the evaluation of generation investment in a competitive environment. The project evaluation includes the multi-agent simulation of electricity market and the economic appraisal. The proposed model architecture is applied in a multi-agent simulation of the spot market (Fig. 7). The main output

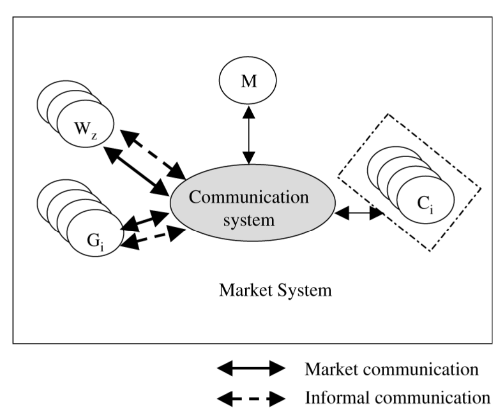

Figure 7. Example of a spot market system with a simple auction (Informal communication may concern coalitions formation).

is the spot price that provides the market signals to the investors. 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.

Three scenarios of market structure are simulated for 20 years. The first market structure is considered as perfect competition, i.e. no market power, while for the second and third market structure, it is assumed that the traders/brokers make coalitions at two different market power levels.

The agents involved in this application example are one market operator agent, one regional transmission organization, several trader/broker agents depending on the market structure, a number of generator agents depending on the market structure and one consumer agent.

4.2 Modelling

The consumers are modelled using a degree 1 synthetic end-user agent that is an association of basic consumer agents. It has the capability to aggregate the load curves and to communicate them to the market operator at the beginning of each daily auction round. The demand evolution constitutes a growth trend with annual growth of 2% and a stochastic component for taking into account its uncertainties. There are 18 generator agents for market structure 1. Table 2 gives the basic information of the generator agents in the system. The trader/broker agents make coalitions of the generator agents to make more profit in the imperfect markets depicted by market structure 2 and 3. Market structure 2 leads to 9 wholesalers and market structure 3 to 5 wholesalers.

The market is assumed as day-ahead simple auction and with uniform price where the generator agents and the trader/broker agents compete to obtain as many as profits through electricity supply to an aggregate demand (Figs. 7 and 8). The process begins with the generators' and traders/brokers' submissions of price and quantity bids, to the market operator for the 24 hours of the day ahead. Once receiving the bids, the market operator allocates the bids in price merit order. The bid price of last unit satisfying the demand is system marginal price (SMP).

Taking into account a capacity element, the market clearing price (MCP) is calculated as follows:

$$MCP = SMP * (1 - LOLP) + VOLL * LOLP$$

Table 2
Generator Agents in the Example System

Agent ID	Plant ID	Plant Name	Plant Type	Plant Size (MW)	Plant Outage (%)	Starting Bid ($/MWh)
0	0	ECG1	CCGT	380	3	12.3
1	1	ECG2	CCGT	405	3	10
2	2	ELC1	COAL	450	5	25
3	3	ELC2	COAL	520	5	26
4	4	EMC1	COAL	450	5	29.3
5	5	EMC2	COAL	450	5	28.4
6	6	MNU	NUCLEAR	1000	5	1.5
7	7	HPS1	P.STORE	350	3	22
8	8	HPS2	P.STORE	350	3	20.9
9	9	NCG1	CCGT	300	3	13.5
10	10	NCG2	CCGT	350	3	12.5
11	11	NLC1	COAL	300	5	16.8
12	12	NLC2	COAL	300	5	16
13	13	NLC3	COAL	300	5	15
14	14	NMC1	COAL	300	5	17
15	15	NMC2	COAL	300	5	16.2
16	16	NSC1	COAL	200	5	18.5
17	17	NSC2	COAL	250	5	19

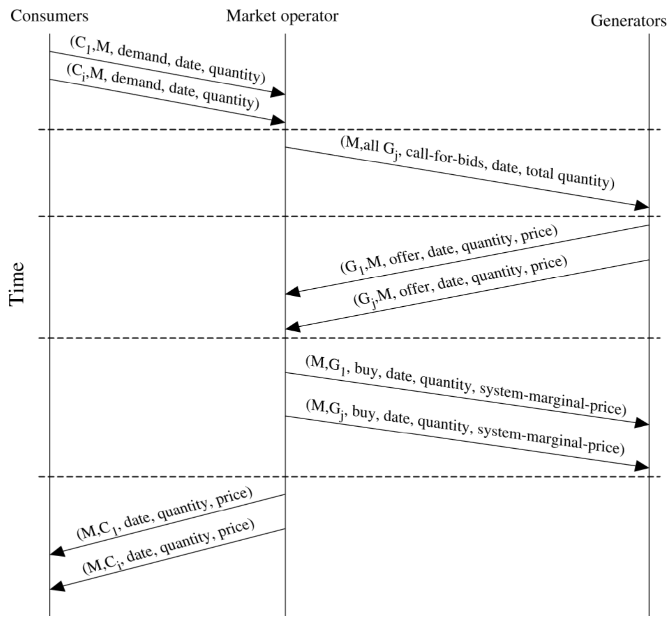

Figure 8. Coordination dialogue in the case of spot market.

where LOLP: loss of load probability [%], VOLL: value of lost load [$/MWh].

Then the market operator publishes market setting and informs the regional transmission organization.

In the auction process, the generators and traders/ brokers adjust their bidding strategies according to the market information. The learning process for bidding strategy is assumed as: in principle, the agent makes price bid based on the marginal costs of the power plants. Nevertheless, it forecasts market price and adjusts the bidding price to maximize the profits of each period. For the bid quantity, we assumed that the agent wants its plants to operate with 100% available capacity.

Price raising and price lowering: at the beginning of each year, the agents make a basic estimation of the market price for each period and make an adjustment on bidding price relative to the price of the corresponding period of the precedent year.

Maximum profit pursuit: during the bidding process, for each period, if the total profit of the previous period did not increase, make a limited random increase on the bid price of the previous period.

4.3 Results

The simulation results of market prices with three market structures are shown in Fig. 9. It can be seen that the price evolution follows a long-term cycle. It may suggest a long-term capacity investment cycle.

When the price is relatively low, the market is not attractive to the investors and the new capacity construction is modest. It will result in a decrease of the system's capacity reserve. This decrease is reflected in the capacity element of the market price that is related to the reliability of electricity supply. When the reserve is low, the reliability indicator LOLP is high and consequently the market price is high. In addition, the generator and trader/broker agents may adjust their strategies for maximizing the profits and this may also make market price to increase. The market becomes attractive to new investment. The generator agents will expand their capacities and this will drive the market price lower down.

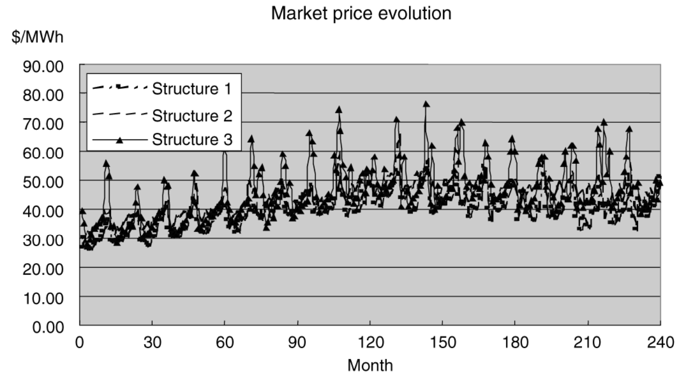

Figure 9. Prices evolution of different market structures.

The imperfect market is modelled through the merger or coalition of generator agents formulated by the wholesalers. This constructs different market structures. The results show that market power makes it possible to increase the price.

This market simulation example demonstrates that agent-based model allows a specified representation of the different actors and their interactions in electricity markets. The actors' behaviours, e.g. the bidding strategies of generator agents, can be simulated in a flexible way that extends the traditional game theory. The market price prospects are made through the simulation that is based on the future situations of electricity supply and demand. This price forecasting provides the basic information for investment decisions.

An investment project of a 300 MW CCGT power plant is evaluated in the market environment stated above. The estimated basic information about the project is shown in Table 3. The power plant sells electricity through bilateral contract and spot market. The spot market price is obtained from the market simulation described above. The bilateral contracting of electricity in a competitive environment is a matter of negotiation. In this application example, the sale portfolio constitutes one bilateral contract and the spot sale. The bilateral contract price is estimated year by year by the investor as the expected market price in the future.

The cash flows of the project are obtained based on the spot prices, the bilateral contract prices and the production costs. The project's internal rate of return (IRR) is calculated and presented in Table 4. Since the IRR is higher than the target rate of return, the project is economically viable.

This application example can be extended to a more complex investment project or situations such as: complementary investment projects, exclusive choice among a

Table 3
Basic Information of the Project

Variable	Definition	Unit	Value
k	Kind of bilateral contracts		1
y	Commercial life of the project	Year	20
h	Operating hours in a year	Hour	7446
hm	Operating hours in a month	Hour	620.5
r	Annual discount rate	%	8
irr_T	Target internal rate of return	%	10
stdpc	Standard deviation of bilateral price, gas price	%	5
bf	Percentage of bilateral selling in total production	%	70
C	Plant capacity	MW	300
I	Investment cost, 500$/kW, invest 50% and 50% resp. at the beginning of year 0 and year 1	$	150000000
FOR	Forced outage rate of the plant	%	3
vom	Variable O&M costs	$/MWh	2
fopcost	Annual fixed operation cost	$/kW, YEAR	16
censm	Cost of energy not served due to forced outage of the plant	$/MWH	150
HR	Heat rate of the plant	GJ/MWh	7.2
pf	Expected gas price	$/MWh	8.8
TAX	Tax on net revenue	%	20
LOLP	LOLP limit	%	0.274
VOLL	Cost of energy not served due to the system outage	$/MWh	2000

Table 4
Results of IRR of the Project

	Market Structure 1	Market Structure 2	Market Structure 3
IRR (%)	12.4	16.2	17.1

set of combinations of complementary projects, option to abandon or to defer, etc.

5. Conclusion

In this paper, a multi-agent architecture is proposed for simulating market oriented activities in the electric supply industry. Based on that architecture, an intelligent decision support system (IDSS) has been designed. Then, the market simulation module has been applied to a case of an economic evaluation of an electric power plant project. The results show the influence the assumptions regarding the future market structural changes have on the economic performance of a project, and thus, on the investment decision. Future research works will consist in a detail specification of the model in complex interactions cases.

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