Smart Meter Aware Domestic Energy Trading Agents

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ABSTRACT

The domestic energy market is changing with the increasing availability of energy micro-generating facilities. On the long run, households will have the possibility to trade energy for purchasing to and for selling from a number of different actors. We model such a futuristic scenario using software agents. In this paper we illustrate an implementation including the interfacing with a physical Smart Meter and provide initial simulation results. Given the high autonomy of the actors in the domestic market and the complex set of behaviors, the agent approach proves to be effective for both modeling and simulating purposes.

Categories and Subject Descriptors

I.2.11 [**Computing Methodologies**]: Distributed Artificial Intelligence—*Intelligent agents, Multiagent systems*

General Terms

Design, Economy

Keywords

Energy trade, agents, smart meter

1. INTRODUCTION

The domestic energy market is experiencing important changes that are driven by both technological advancements and the introduction of new policies. On the one hand, micro-energy generation facilities are becoming economically attractive and are spreading [11, 12]. On the other hand, a clear trend of market unbundling is emerging (e.g., [5, 8]) entailing the addition of many new players to the energy sector with the possibility to produce, sell and distribute energy.

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The term *Smart Grid*, which does not have a unique agreed definition yet, is sometimes used to define a new scenario of the Power Grid with a high degree of delocalization in the production and trading of energy. The new actors, who are both producers and consumers of energy, are referred to as *Prosumers* and are becoming more numerous. Up to now, these Prosumers are forced to either consume the energy they produce, store it (which is very inefficient) or put it back into the grid getting a payment from the Network Operator. If the number of Prosumers will increase considerably, as it is expected, they will most likely demand a market with total freedom of energy trading [19]. But how would such a market operate?

In this paper, we address this issue by providing an agent-oriented modeling of the domestic energy market. The motivation for this choice is that the energy actors are independent one of another, they have complex behaviors necessary to maximize the individual profit/savings while maintaining a stable energy provisioning for the household they trade energy for. Furthermore, the future Smart Grid is seen as an infrastructure of bidirectional information exchange, where every node sends consumption information, but also generates information or even provides means for remote controlling. This is an additional set of behaviors that are well modeled by an agent-oriented approach.

We concretize our proposal, by providing a set of abstract agent descriptions, together with an illustration of an implementation based on a well-known software platform. Behaviors of agents are described in detail including how they form strategies. Then we illustrate a simulation we have performed with software agents which also interface with a real element of the Power Grid. The rest of the paper is organized as follows. In Section 2, we present the abstract model of the domestic energy market while Section 3 provides a description of the main and auxiliary agents operating in it and how they communicate. The implementation using the JADE platform and a Smart Meter is described in Section 4. Preliminary simulation results with tens of agents are described in Section 5. A detailed view of the agent roles is offered in Appendix A.

2. DOMESTIC ENERGY MARKET

Given the unbundling of the energy sector and the availability of micro-generating facilities, it is easy to foresee a radical change in how the domestic energy market will work. An essential characteristic of this type of market is the relative large number of negotiating intervals comparing to the current situation of energy contracts usually with yearly duration. We present next a model that fits well the future scenario and allows the simulation of trading agents.

The dynamism of the future energy market is represented by dividing the day into several time intervals with same length in which energy can be bought and sold. In particular, during each negotiation round energy is contracted for the following time interval. The time intervals can be of several hours, but can also be as short as few minutes. In the following simulation, we shall consider days divided into six intervals.

In the market, we distinguish a number of roles. The fundamental actors in the market are few traditional big generating companies (a.k.a. *Gencos*), a limited number of *Prosumers* that are able to produce small quantities of energy compared to Gencos and a high number, compared to Gencos and Prosumers, of *Buyers* that are interested in purchasing energy at the cheapest price possible. The market also contains a third party authority, known as *Balancer*, which has information about the quantities of energy produced and demanded by the various parties. Its role is to act as a intermediary with the aim of maintaining as much as possible the energy balance equilibrium on the Power Grid.

In such a model, the described actors have, possibly conflicting, goals. The Prosumers have the goal to sell any surplus power on the energy market at the highest possible price. However the price is usually significantly lower than the price offered by the Gencos. In addition, the main constraint is that the power provided by Prosumers is not sufficient to supply the whole demand, but only a fraction of it. The Gencos have the goal to sell energy optimizing price per unit, that is, since production costs do not grow linearly, they want to sell energy at the price yielding the highest possible revenue for them [14]. The Balancer has the goal to keep (a geographically identified portion of) the market in balance to avoid failures on the grid, so the amount of demand should be met by the offer by the Prosumers, backed up by the Gencos.

In order for the Balancer to have the most possible exact data, an important aspect is energy forecasting both for demand and for production through small-scale equipment. The forecasting of the amount of energy supply a single Prosumer can offer during a certain negotiation round is based on meteorological data (namely, wind strength, sky visibility, atmospheric pressure and other parameters relevant for energy production [15]) and on parameters related to the quality of the Prosumers' micro-scale generating equipment (e.g., solar panel efficiency, small-wind turbine cut-in and cut-out wind speed). Calculating the sum between every capacity of every Prosumer, the external Balancer entity can forecast the amount of extra energy that needs to be produced by the Gencos to satisfy the expected demand.

Before defining the agents in detail, we provide a more precise explanation of what is meant by keeping the market in balance. We do this resorting to a simple balancing equation showing the relation between the total energy demand of an area and the supply capacity of the sellers for that area. There are several mathematical models to describe balancing equations (e.g., [9, 10, 17]), though all have the same basic underlying idea which is to set to zero the algebraical sum between energy demand and supply.

Let $D_{\Delta t}$ be the sum of all the demands of all consumers in a given time interval, we define its balancing equation as

$$D_{\Delta t} = \sum_{k=1}^{C_{\Delta t}} D_k = \sum_{i=1}^{N_g} S_{\Delta t}^{Gc_i} + \sum_{j=1}^{M_p} S_{\Delta t}^{Pr_j} \tag{1}$$

where:

- $C_{\Delta t}$ is the number of consumers at time interval Δt;
- D_k is the energy demand by the k^{th} energy Buyer;
- S^z is the energy supply provided by z^{th} source of energy;
- N_g is the total number of number of Gencos;
- Gc_i is the i^{th} Genco;
- M_p total number of Prosumers; and
- Pr_j is the j^{th} Prosumer.

The equation simply states that the sum between the two different production sources (Gencos and Prosumers) should be equal to the total consumer demand. As we said this is a reasonable modeling of the balancing which though does not consider energy losses in transportation and production, forecasting errors in demand, nor any quality of services of the energy producers. That is, the reliability of a power source does not matter in the equation. As for prices, we assume that the ability of producing a certain amount of energy is influenced mostly (especially from a price perspective) by the market of raw materials for Gencos, while the Prosumers have to deal with the local weather.

From the practical point of view, $S_{\Delta t}^{Pr_j}$ is estimated by the forecasting algorithm [2, 15], $S_{\Delta t}^{Gc_i}$ can be controlled by asking the Gencos to produce more or less energy, and $C_{\Delta t}$ is estimated based on past consumptions [6, 13].

3. AGENT MODELING

From the global view of the market, we now move to the agents' perspective and consider how to model each agent's behavior and its communication capabilities. First, we distinguish between *main* agents, those representing energy consumers and energy generators, and *auxiliary* agents which do not directly deal with the energy purchase and sell, but provide information and mediation to support the behavior of the main agents. Second, we consider the agent roles. The main agents are:

- *Consumers:* which buy energy.
- *Prosumers:* which produce and consumes electricity being able to both buy and sell it. They can produce a limited quantity of energy (compared to a Genco) thanks to micro-scale energy production devices such as small wind turbines, solar panels and micro-CHP.
- *Gencos:* sell energy at various scale. These are the traditional big energy generating companies which can be or not also in charge of the distribution of the energy.

As for the auxiliary agents, we initially identify three:

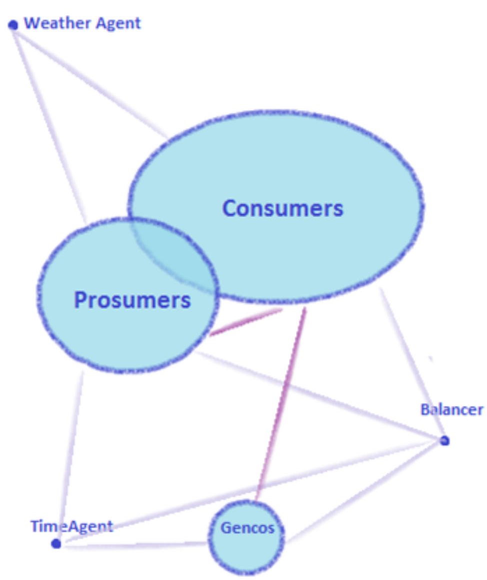

Figure 1: Diagram representing agents of the architecture and the interactions between them.

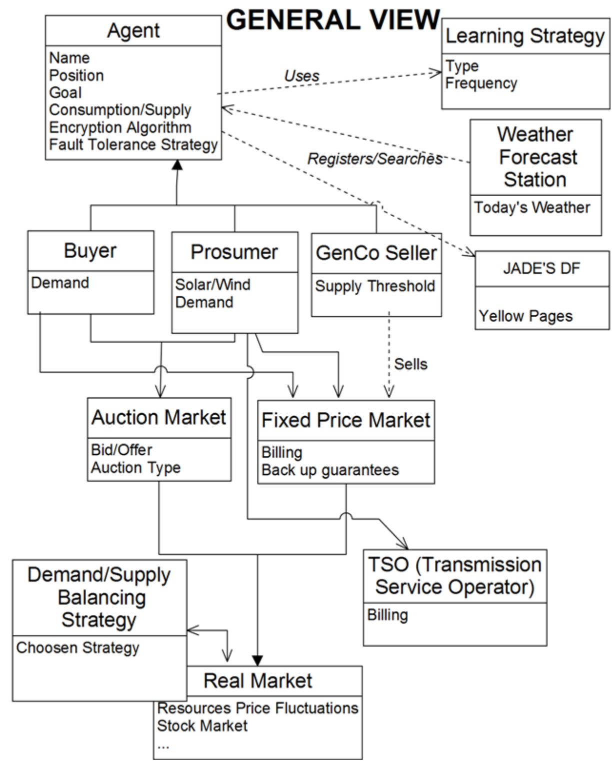

Figure 2: Class diagram of the main agents involved.

- *Balancer:* has a mediating role among main agents to keep the balance of offer and demand.
- *Time Agent:* defines the starting and closing of a time interval as defined for Equation 1.
- *Weather Agent:* provides localized information about weather forecast, especially parameters useful to predict micro-scale generation.

Figure 1 provides an illustration of the main agents as ovals and the auxiliary ones as dots.

In addition to the just defined agents, for the simulation purposes, two more agent roles need to be defined as we resort to the JADE (Java Agent Development Environment) [3, 4]. The details of the choice will be explained in Section 4, here we just introduce the necessary agent roles. The first agent created is the *Creator Agent* that generates all the other agents. Another essential agent that is present in the architecture is the *Directory Facilitator Agent (DF)* that provides a yellow pages-like service for the platform. A detailed description of the agents' behaviors is provided in Appendix A.

To better understand the agents' features and relations, we provide a class diagram with the general view in Figure 2. Every agent is defined by multiple parameters. Some of them are common, others are specific for the role chosen by the agent. Variables' name should be self-explanatory, with perhaps the exception of the *position* variable that characterizes any agent. It refers to the areas the city (or region) considered in the simulation is divided into. In the simulation we consider six sub-areas: every area has its own identifying number (from 0 to 5) that represents also the distance between different agents. Distances simulate the different costs of transporting a single energy unit from one area to another. In fact it is reasonable to think that in the future also the services related to energy transmission and distribution will be completely unbundled by generating utilities and managed by other entities whose services will be paid separately. Therefore distances are related to Transmission System Operator (TSO) or Distribution System Operator (DSO) contracts and every seller may have a different TSO/DSO operator that charges the producer a certain amount of money for transporting energy from one area to another. The bigger is the distance, the higher gets the price. Obviously the prices paid by sellers (Prosumers and Gencos) will influence the final price that they are going to propose to their possible Buyers. Every agent in the simulation has a random position that defines then the distance to producers and therefore TSO/DSO related prices.

3.1 Agent interactions

All the interactions between agents are represented by message exchanges between them. The message exchanges need to be standardized in order to make sure that any new agent can join an existing infrastructure. We chose to go for the most accepted standard for agent communication, the FIPA one[1]. We consider two kind of messages: synchronization messages and market related messages.

From the implementation point of view, the chosen platform (i.e., JADE) follows an asynchronous message passing paradigm and it is based on the Agent Communication Language (ACL), while being fully FIPA compliant. Every

[1] http://fipa.org/

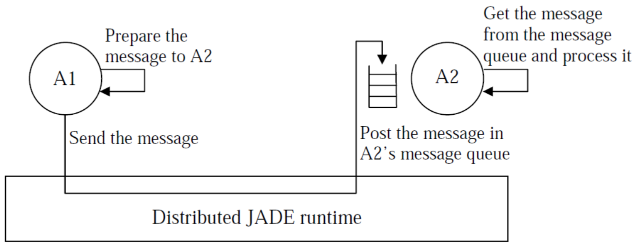

Figure 3: A representation of message passing communication in JADE.

agent has a queue that stores the incoming messages, the extraction of the message from the queue is then up to the programmer. The typical situation of message exchange is depicted in Figure 3.

The essential parts composing a message according to the FIPA/ACL language are:

- *Content* is the payload of the message itself.
- *Performative* represents the purpose of the message, or better the communicative intention. Independently from the content, an agent could decide to try to better understand what a sender is saying by just fetching this part of the message. In particular, for the energy exchange architecture we propose, we consider the following constructs:
  - INFORM and INFORM_REF performatives represent generic informative messages used for synchronization purposes. The latter is used as synchronization signal for final operations (e.g., a Buyer informs a Balancer that he has stipulated a contract successfully).
  - PROPOSE, REFUSE and ACCEPT_PROPOSAL performatives are used in market related messages. The first one is used for a bid proposal sent by a Buyer agent or provides information about starting price of a negotiation when sent by a energy seller agent. The second performative is used to refuse a single offer, while the last performative is used to accept an offer proposal.
  - CANCEL performative is used by a Prosumer in order to abort the current auction with the specified Buyer.
- *Language* represents the syntax used to express the content, however this aspect is not used in our project.
- *Ontology* represents the knowledge representation of the domain. This aspect is not used in the current version of our project, though will be considered in future extensions.

FIPA standards are not just related to the message format, but they also give information about how to name an agent in a distributed and heterogeneous platform. For brevity, we omit the formatting of these aspects here.

3.2 Agent behavior in the market

In the domestic energy market, all the agents have a specific goal, as we presented in Section 2, that is, trade a good and maximize profit. Therefore, the agents are competing against each other for obtaining the energy at the best price and selling it at the highest one. The actual contracting is based on an auction system in which all main agents participate at every round of trading. Thus the situation is as follows.

- A Buyer can stipulate a contract with a Prosumer after winning an auction round, realized with sealed bids; every Buyer can send several offers to suitable Prosumers in any given round.
- Prosumers' energy starting price is considerably lower than Gencos' initial contract prices.
- Weather conditions during an observed interval can prevent a Prosumer to generate enough electricity to be sold.
- Prosumers communicate to Buyers an initial starting price that is influenced by contracts with energy transmission and distribution operators and a random cost due to the devices used to produce electricity (e.g. maintenance costs).
- The energy produced by a Prosumer has to be sold quickly and cannot be stored or buffered for selling at a later round.

Every Prosumer is in direct competition with other energy sellers therefore they propose an appealing starting price and make an intelligent use of refusing bids in order to rise the price without letting Buyers contact other sellers. On the other hand, Gencos are big energy generating companies and they have a theoretical infinite amount of energy supply, but they also have some peculiarities to be taken into account:

- Gencos sell energy with contracts lasting for one time interval or more at a given fixed price.
- Gencos contracts can be stipulated much faster since there is no auction.
- Gencos prices are in general higher than Prosumers' starting prices.
- Gencos prices depend on exceeding production threshold known a priori. This implies that energy exceeding the threshold will be more expensive for the Genco and thus for the Buyer. This models the fact of putting into operation extra power plants to compensate an excessive demand is costly. Therefore, the unit price of energy the Gencos sell on the market can be represented by the following threshold function:

$$E_{uc} = \begin{cases} Cost_{energy} & \text{if below supply threshold} \\ Cost_{energy} \times (EC \times A) & \text{otherwise} \end{cases}$$

  where $EC > 1$ is an external costs constant and $A \in \mathbb{N}_1$ is the number of energy units above the threshold. Asking Gencos energy contracts when the threshold is already surpassed leads to more expensive contract prices. Those prices rises as we get further from the specified threshold.

In these conditions, the challenge is strictly related with the ability of agents to quickly obtain an energy contract either with a Prosumer or with a Genco since as time passes it is more likely that Gencos will exceed their production threshold thus increasing the price of a contract. In fact, if every Buyer follows a natural strategy that brings him at contacting the Prosumer first hoping in cheap contracts, he is then involved in spending time in the auction process with offers and bids rising. If no contract with a Prosumer is found it is likely that the Gencos in the meanwhile have exceeded their threshold and only high priced energy is available.

A modeling of the best strategies for the agents, is beyond the scope of the present treatment which aims at providing a modeling and a software platform for the domestic market. We remark however that the family of minority games is a good way of representing the interaction and finding suitable agent strategies in such a market. In minority games, two different behaviors for a single player are admitted and s/he wins if s/he chooses the path taken by the minority of the players. Applying this game to the domestic energy market means that each Buyer Agent can learn and adjust its behavior (i.e., contacting a Prosumer or a Genco) reducing the average cost of energy paid by the Buyers [1]. In particular the most similar game theoretic approach that present a situation similar to the one just explained for the energy market model developed is the *El-Farol-Bar* problem [7]. It is possible to use the solution identified for the *El-Farol-Bar* game by Whitehead [21] and extend it to take into account the even higher level of complexity of the energy market model presented here [1].

4. IMPLEMENTATION

To evaluate the proposed model and perform simulations of domestic energy markets, we have implemented the proposed architecture with a well-known agent platform. To make the evaluation even more realistic, we have used data coming from a home use equipped with a Smart Meter. Next we describe the implementation.

4.1 The JADE platform

Recent studies [16, 18, 20] have compared agent platforms on the basis of a number of parameters. Among these, one has emerged as excelling when considering general purpose uses [3, 4]. The JADE (Java Agent Development Environment) is a software middleware framework implemented in Java language which is fully FIPA compliant and it comes with a set of useful (graphical) development tools [3, 4]. Among the strong points of JADE are the standard compatibility for agent messaging and the compliance with FIPA specifications from a communication perspective. In addition the mobility properties (data persistence when an agent is migrated between hosts) and the easy adaptation to high distributed environments are important points for a negotiation oriented platform. Open source code and the abundance of extensions are other strong points of this agent development environment.

4.2 Smart Meter interaction

We focus on the Dutch case, as this is the location where the research has been carried out. In the Netherlands, there are strict regulations regarding the functionalities of a Smart Meter and especially on what outputs are allowed. In addition, there is the requirement that customers can switch from one energy supplier to another without replacing the Smart Meter. The Dutch Normalisation Institute (Nederlands Normalisatie Instituut) is in charge to provide the set of design requirements for the Smart Meter , which resulted in the Dutch Technical Agreement (Nederlandse Technische Afspraak 8130) released on April 30, 2007. Let's consider the most notable of these:

- Providing remote information about consumed and supplied energy;
- Remote disabling and enabling of capacity;
- Measure and identify quality of network;
- Online interaction between consumer and supplier; and
- Fast reaction with energy installations for load management.

In technical terms, this translates in having four different communication ports, also known as *P ports*, on any Smart Meter . These are:

- P1 is used for the communication between the metering installation and one or more other service modules, but it cannot be used for sending data to the metering system.
- P2 is used for the communication between the metering system and from one up to four metering instruments and/or grid operator equipments.
- P3 is used for the communication between the metering installation and the Central Access Server (CAS[2]).
- P4 is the port on the CAS where independent service providers, suppliers and grid operators gain access to the CAS. The stored information is accessible via as an XML-based Web service.

In the context of the present treatment, the port P1 is the most interesting one because external modules can read data from the Smart Meter. This port should be implemented over an RJ11 connector and communicate with the NEN-EN-IEC 62056-21 standard with a baudrate of 9600 baud.

Figure 4: The Itron ACE4000 GSMM Smart Meter.

[2]The CAS is a centralized server where all consumption data from connected Smart Meter is stored.

The Smart Meter used in the project is Itron ACE4000 GSMM (shown in Figure 4) which complies to the Dutch technical requirements. Since all Smart Meters have to follow the same requirements, the choice does not limit the generality of the approach and was dictated by the availability of one of such meters.

The meter though, does not provide directly the information needed by the agent and in the right format. Therefore, we have realized an embedded device in collaboration with the Electronic Engineering department of the Hanzehogeschool Groningen that enables the interaction between the Smart Meter and the agent platform. The device is shown in Figure 5. The function of the embedded device is to translate the serial communication and information that are provided by the Smart Meter through P1 to a interface that is easily addressable by the software agent, cf. Figure 6. In particular, the embedded device has a Web server interface that enables the software agent to request information about the Smart Meter with standard HTTP messages. The embedded device stores the information that are periodically pushed by the Smart Meter towards P1 port. The messages are encoded in XML to ease parsing by the software agent and to be extensible for future use of the gateway. An example of a message sent by the embedded device is given next.

Figure 5: The Smart Meter gateway.

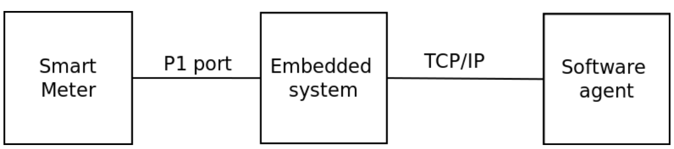

Figure 6: Block diagram of the communication between Smart Meter, embedded device and agent.


```
<form>
<m_name>SmartMeterSim</m_name>
<m_iden>0505514284290634</m_iden>
<eu_low>489.777</eu_low>
<eu_normal>489.777</eu_normal>
<ep_low>.114</ep_low>
<ep_normal>.114</ep_normal>
<t_indic>normal</t_indic>
<e_watt> 60</e_watt>
<cost>0.01</cost>
<time>11-01-24.10:21:44</time>
</form>
```


Besides the information related to the Smart Meter such as name and serial number (respectively *m_name* and *m_iden* fields) the message also contains information such as the total energy used in kWh both in off-peak and peak periods (respectively, *eu_low* and *eu_normal* fields) and the total energy produced during off-peak an peak period (respectively, *ep_low* and *ep_normal* fields). The rest of the message is information about the type of the available tariff which is normal or off-peak (*t_indic* field), the energy cost per kWh (*cost* field) and the instantaneous power consumption in Watt (*e_watt* field). A time stamp (*time* field) is also provided.

The Buyer Agent receiving messages from the Smart Meter can be informed about previous and current consumption of electric energy and use the information to forecast the energy demand. The agent can also update the meter with the prices related to energy once the agent has finished to stipulate a new energy contract (this last feature in the simulation is limited by the unidirectionality of P1). From an implementation point of view, the agent needs the ability to send GET HTTP requests towards the embedded device's IP address and be able to parse the XML information provided by the embedded device. The extracted data are then used to set the agent parameters used for following energy negotiation.

5. SIMULATION

To test the model proposed and to evaluate agent strategies, we have simulated market behaviors based on the implementation just described. The simulations is realized on a machine with AMD Athlon II Dual Core M300 2GHz processor with 6GB RAM running a Windows7 64-bit edition. The Java version installed is JAVA SE 6 Update 21 and the JADE environment is JADE 4.0.1. The Smart Meter is connected to the gateway and accessible by the platform on one end, on the other end is connected to the main meter of a home where three students of the Hanzehogeschool live.

We simulate a market with a single Enhanced Buyer connected to the Smart Meter, 29 ordinary Buyers, 7 Prosumers e 3 Gencos, with six geographical areas and six time intervals per day. Every type of agent has different duties inside the system. Some of those duties are "real world-related", that means we are referring to behaviors directly connected to the operations of the real energy exchange system market (e.g., finding the best seller/buyer). Other behaviors are created in order to set the simulation environment. They have been implemented in order to analyze and realize the whole simulation system (e.g., graphic user interface implementation). The main differences in the behaviors between the simulated system and real implementation are represented in Figure 10.

An example is given by the Weather Agent that at the moment randomizes weather while in a real implementation should retrieve forecasting for instance from a meteorological Web service available on the Internet. There are also some parts of behaviors that are shared between the two worlds, that is both in the real world and in the simulation environment the system has to be aware of certain variables (intersections between sets in Figure 10). All the Buyers (except one) are randomizing data about previous consumption, these data are essential for energy forecasting aspects. In the real environment consumption data should be gathered by interconnecting with a Smart Meter device; in our experiment only one Smart Meter is available and installed in a real domestic context and is able to interact with one agent (called Enhanced Buyer).

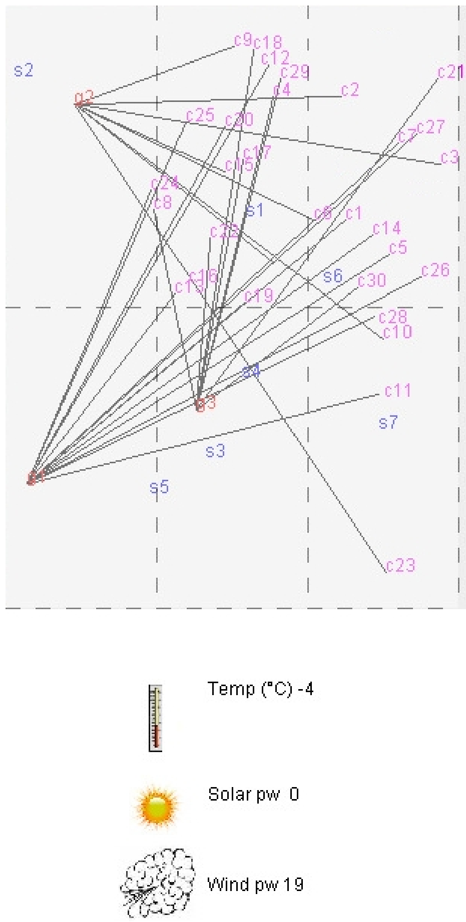

Figure 7: Representation of the contracts that have been concluded by consumers and suppliers.

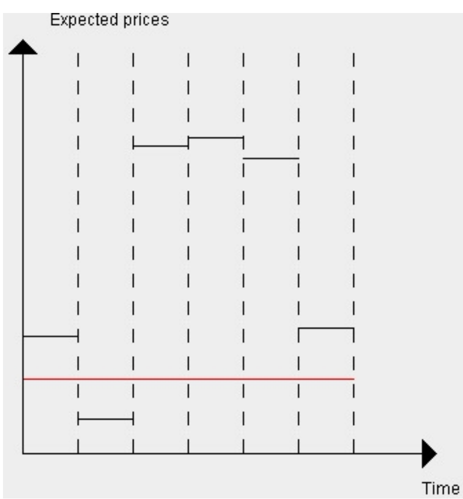

Figure 8: Evolution of the price paid per energy unit for a Buyer Agent with no learning strategy implemented. Red line is the estimation in price at the beginning of the negotiations and black lines are the actual price paid in the negotiation.

Figure 7 shows a graphical snapshot of the simulation together with the values of external weather conditions. Every market participant is represented by a point in the map of the city (or region) considered which is divided into several zones (dashed lines are zone boundaries). Buyers are represented in purple and their identification prefix is "c", Prosumers are represented in blue and their identification prefix is "s" while Gencos are represented in red and their identifier starts with "g". All the black lines in Figure 7 are connections that indicate an agreed contract. In the particular simulation run shown in the figure, no Prosumer succeeded in selling energy, most probably due to bad weather conditions. The platform also provides the possibility of checking the evolution of the price paid in each negotiation round (this is available by clicking on a node). Figure 8 shows an instance of such evolution where black lines in each time interval represent the price paid for energy in that interval, the red line represents the expected price the Buyer would have paid. We see that in this situation the difference between the price paid and the expected price can be quite significant. The reason for this is that, in the shown simulation, the agent generates the expected price randomly at the beginning of the simulation.

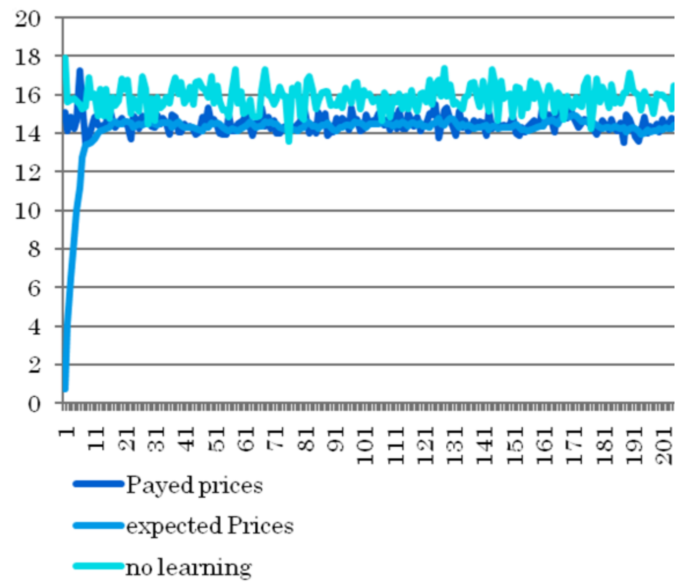

Figure 9: Difference in average price paid without any learning and with introduction of learning strategy for buyers (first 200 negotiation rounds are shown). X-axis represents the negotiation round, while y-axis represents the average price paid for an energy unit.

Naturally, a better strategy for the agent is to generate an expected price based on the past experienced prices. To do so, it has to be enhanced with a learning algorithm. We performed a second set of simulations with the aim of evaluating learning strategies, cf. [1] for details. In the simulation 100 Buyer participants, 10 Prosumers and 5 Gencos interacting over 400 market negotiation rounds have been used. The condition simulated consist of Buyers playing on the market without the learning strategy and then in the same conditions following the learning strategy to contact suppliers. The results are shown in the Figure 9 which highlights the gap between the two situations: with no learning the average price paid (light azure line) is higher than when the agents use learning algorithm to place their bids (blue line). In addition, one can see how expected prices (light blue line) initially start very low (i.e. prices that are not realistic) and then reach values that are in line with the market, following quite well the average contracted value.

6. CONCLUDING REMARKS

The way in which energy is provisioned and generated in the domestic market is changing and a future in which any household can provision from a number of actor based on a short term auction system is not unlikely. In this paper we have provided a model based on agents to describe the interaction among households and large generating facilities. The model is implemented by the well-known software platform JADE and we have illustrated some preliminary simulation runs to evaluate different settings and strategies for the agents. The platform can interface with external software or physical devices.

The initial simulation has highlighted the feasibility of the approach, while also leaving room for many improvements; among these, we plan to consider in more detail the security aspects (e.g., secure connections with the smart meters, and among the trading agents), to study the scalability of the approach, and we want to deepen our knowledge in several learning strategies and properties of the game models.

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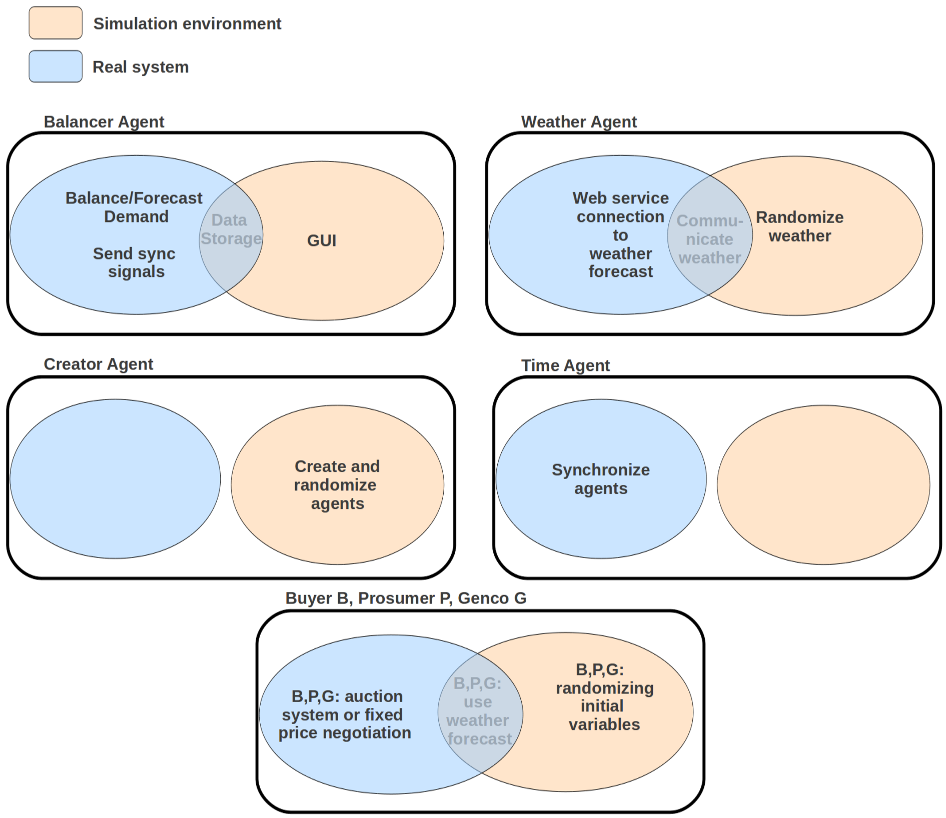

Figure 10: Differences in agents' behavior in simulated and potential real environment.

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APPENDIX

A. DETAILED AGENT DESCRIPTIONS

Each agent identified in Section 3, has a specific role, set of behaviors and implementation rationale. Next we list the agents together with such detailed information.

Creator Agent

The Creator Agent is responsible for creating other agents that interact on the energy trading market. In addition it sets-up the platform simulation environment. Once finished with creation it terminates.

Weather Agent

The role of the Weather Agent is to provide a weather forecasting service. It gives important information to Prosumers such as temperature, solar incidence power and wind strength. In this version of the energy trading platform this information come from a random generation. Once registered to the DF service the main task of the agent is listening to messages containing INFORM perfomative with a specific request over weather condition; once triggered by this kind of message the agent replies to the agent that has sent the request. It can be based on existing Web service-based-services available on the Internet.

Time Agent

The main goal of this agent is to provide the current time to other agents that need this service. Of course this agent too registers himself in the DF to be known to other agents. It also may send an end of time message (EOT is an INFORM perfomative message with a special payload) to the Balancer Agent to inform the approaching of the end of the negotiating interval.

Balancer Agent

The Balancer Agent is essential for the whole proper market functioning. It is a central authority that has the information about everything that is going on the market. After registering himself to the DF service, it searches also in the DF for the presence of Time and Weather Agents. After finding these two essential agents for the market system it looks, once again in the DF, for agents with generating capabilities (i.e., Gencos and Prosumers). It sends them a message to be informed about their name and position. In particular if the communicating agent is a Prosumer the Balancer receives also an information about the amount of energy the Prosumer expects to produce in the following time interval. Almost the same set of information are requested when Balancer finds a Buyer Agent in the DF: position and a forecast about the demand in next time interval are required. Having all the information about the small-scale production and demand, the Balancer can then provide the Gencos with a production threshold, this is realized by sending each one a performative INFORM message containing the suggested threshold. Another duty of the Balancer is to listen for CONFIRM perfomative messages that Buyer Agents report him once contracts are completely negotiated. In addition if he receives a EOT message, he sends to all Buyers without contract an INFORM performative message forcing them to stipulate a contract with the closest Genco agent. The Balancer provides also the entire market with the start of negotiation signal.

Buyer Agent

The Buyer Agent can be *regular* or *enhanced*, that is, a completely simulated behavior agent (regular) or one interacting with a physical Smart Meter that gathers energy consumption (cf. Section 4.2). As all other agents participating to the market operations he registers to the DF service looking for the presence of Time, Weather and Balancer Agents. He then waits for an incoming message from the Balancer that asks for the position and demand forecast for the following time interval; once replied the Buyer waits again for the signal of the start of the auction. When the auction is started the Buyer asks every energy producer the price of energy through an INFORM performative message containing Buyer's name and position. At the same time the Buyer asks every Genco about their position to locate the closest one. From the list of all sellers the Prosumers that have not enough capacity to satisfy the needs of the Buyer are discarded. If the set of sellers does not contain any Prosumer then the Buyer is forced to contact a Genco otherwise he starts contacting the cheapest seller (usually a Prosumer) after having defined the expected budget he intends to spend (this is done by adding a random percentage to the cheapest seller starting price). Once the offer is sent through a PROPOSE performative message, the Buyer waits for the seller's reply. The situation can then evolve in four situations based on the message received:

- ACCEPT_PROPOSAL message: the transaction is then positively closed and the details of the contract are sent to the Blanacer.
- REFUSE message: the seller refuses the bid. The Buyer may contact the same seller again raising his offer and send another bid or, if the price has raised higher than the buyers budget, he discards the actual Prosumer with a CANCEL performative message. He proceeds identifying another Prosumer and starts again the bidding process.
- CANCEL message: this is the message that aborts the negotiation. This situation happens when the Prosumer seller has run out the energy capacity that he is able to produce; the buyer then removes the Prosumer from the set of possible sellers.
- SUBSCRIBE message: it is a INFORM performative message sent by the Balancer to inform the buyer that too much time has passed and since it has not reached an agreement so far he is invited to establish a contract with the closest Genco as soon as possible.

Prosumer Agent

As all the other agents involved in the market, the Prosumer Agent registers himself in th DF service and then searches for Weather and Time Agents. Once he has the information about the Weather Agent he contacts it with an INFORM performative message with a specific payload that asks for the weather forecasting. This info enables him to have a forecast of the amount of energy to be produced with his small-scale energy equipment. Once calculated the energy that will be produced, the Prosumer is then ready to communicate this information to the Blanacer once the request from the latter is received. Completed this step the Prosumer waits to be contacted by a Buyer Agents that submits offers. The number of offers the Prosumer waits before taking a decision is a parameter that he sets in the DF service and so available to the market participants. Once the offers are collected the Prosumer discards all the offers except the highest one with a REFUSE performative message. If the highest offer meets the earnings criteria (or the strategy) of the Prosumer it will be accepted and a reply with an ACCEPT_PROPOSAL performative will be issued; otherwise a REFUSE message is delivered and the Prosumer returns listening for new offers.

Genco Agent

As already described for the other agents operating in the energy market, Genco Agent too registers himself in the DF service and searches in the same yellow pages service for Weather and Time Agent. He then waits for the initialization message from the Balancer to which he replies with its name, position and maximum available capacity. His following behavior still imposes the Genco to wait to receive an INFORM message by the Balancer specifying the suggested production threshold for the following time interval. Genco then just listens and waits for contracting request from Buyers. After each received proposal he replies with a price that depends on the position of the Buyer (i.e., the distance from the generating facility) and the exceed (or not) of the suggested production threshold.