České vysoké učení technické v Praze
Fakulta elektrotechnická

Katedra kybernetiky

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

Student: Mikhail Gudyrin

Studijní program: Softwarové technologie a management

Obor: Inteligentní systémy

Název tématu: Multi-agentní aplikace pro řízení elektrického microgridu

Pokyny pro vypracování:

1. Provedení rešerše existujících způsobů obchodování na energetických trzích.
2. Seznámení se se zvolenou multi-agentní platformou.
3. Návrh a implementace energetické burzy s využitím zvolené multi-agentní platformy.
4. Návrh způsobu, jakým budou spotřebitelé určovat množství a cenu poptávané energie.
5. Návrh způsobu, jakým výrobci budou odhadovat množství a cenu v budoucnu produkované energie.
6. Návrh a implementace komunikačního rozhraní pro obousměrnou interakci mezi simulátorem a multi-agentním řídicím systémem microgridu.

Seznam odborné literatury: Dodá vedoucí práce.

Vedoucí bakalářské práce: Ing. Petr Kadera

Platnost zadání: do konce zimního semestru 2013/2014

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V Praze dne 10. 1. 2013

Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Cybernetics

BACHELOR PROJECT ASSIGNMENT

Student: Mikhail Gudyrin

Study programme: Software Engineering and Management

Specialisation: Intelligent Systems

Title of Bachelor Project: Multi-Agent Application for Control of an Electric Micro-Grid

Guidelines:

1. Investigation of approaches used in energy markets.
2. Familiarization with the chosen multi-agent platform.
3. Proposal and implementation of the energy market using the chosen multi-agent platform.
4. Proposal of methods to estimate price of bids for future energy consumption.
5. Proposal of methods to estimate future energy production of producers.
6. Design and implementation of the communication interface to connect the application with the simulation.

Bibliography/Sources: Will be provided by the supervisor.

Bachelor Project Supervisor: Ing. Petr Kadera

Valid until: the end of the winter semester of academic year 2013/2014

prof. Ing. Vladimír Mařík, DrSc.
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Dean

Prague, January 10, 2013

Czech Technical University in Prague

Faculty of Electrical Engineering

BACHELOR THESIS

Mikhail Gudyrin

Multi-Agent Application for Control of an Electric Micro-Grid

Department of Cybernetics

Thesis supervisor: Ing. Petr Kadera

Prague, 2013

Statement

I hereby state, that I have completed this thesis on my own and I have properly specified all the information sources used, according to the Guideline about observance of the ethical principles concerning university theses.

In Prague, 24th May, 2013

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V Praze dne 24.5.2013

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Abstract

This thesis deals with appliances of multi-agent technology for the control of small energy networks. In such kind of network energy consumption varies significantly during the day, because of the small number of participants. It is reasonably that the price will also change according to the actual generators load. Based on the multi-agents technology and JADE framework we have designed simulation and control program for such electrical grid. In the simulated community there were four small power plants (one gas, two wind and one solar) and eleven homes. Each object had been simulated by individual agent, what corresponds to the distributed nature of the electrical networks. For determining of optimal price for energy we have used a principle of commodity exchange, which had been realized by the specific agent. Results of our simulation were expected – the result energy price was depending on the availability of renewable energy sources, which was changing based on the weather.

Abstrakt

Práce se zabývá použitím multi-agentních technologií pro řízení malých elektrických sítí. V takové síti se spotřeba energie hodně mění během dne, kvůli malému počtu účastníků. Je rozumné, aby se také cena za energii měnila v závislosti na momentálním zatížení generátoru. Na základě multi-agentních technologií a platformy JADE jsme navrhli simulační a řídicí program pro takovou sít'. V komunitě, kterou jsmesimulovali, byly čtyři malé elektrárny (jedna plynová, dvě větrné a jedna sluneční) a jedenáct domů. Každý objekt byl simulován jedním agentem. Pro zjištění optimální ceny energie jsme použili princip komoditní burzy, která byla také realizována jako agent. Výsledky simulace odpovídali předpokladům - výsledná cena na energie výrazně záležela na okamžité dostupnosti obnovitelných zdrojů, která se měnila na základě počasí.

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1. Introduction and background

In the last century humanity has significantly advanced in almost all technical areas. Scientists and engineers nowadays can develop feasible solutions to very complex problems. For example, today we are able to build planet-scale communication and distribution networks, transportation networks, very reliable airplanes, trains, power plants, spaceships, there is a development of technology which will able us to harvest minerals on meteorites moving near the Earth. If reader would try to think, how such things can work, it will be immediately clear, that all of them need advanced multi-level control all the time.

It's obviously, that human cannot control processes in a power plant core or in a vehicle engine, but simple electrical circuits perfectly do it, they are fast and accurate, never tired and so, human are released for higher-level management. But, what if we connect power plants into groups, which have to behave like units, and then, what if we connect these groups into whole global system?

Now, let's look at the groups of units, in our example, power plants. Each power plant has its energy generation core, machinery, cooling subsystem, emergency accumulators, inner power lines, some small generators for self-healing and so on. All these subsystems are controlled and maintained by power plant itself according to its goals. When we are talking at the level of power plants, their goals are clear: to maximize profit and minimize costs. If we connect some power plants into a group, then to the goals of each unit, will be added a new, more global goal of the entire group. It can be, for example, distribution power lines load balancing, according to the geographical positions of power plants it consists of. So now, our units must consider not only its own interests, but also interests of all others in the group. But, power plants are rather "static" objects; there are no each millisecond changes of its states, which require a mission replanning. Theoretically, it still can control a group of humans (but practically cannot).

Now consider a group of trucks which have to transport goods from warehouses to groceries. It is a very dynamic system: trucks are moving on differently loaded roads, people in stores buying goods, all this occur in a real time and permanent and most of these passages are not predictable. States of objects, system consists of, are changing in a very small time samples and each change can engage a mission replanning, e.g. in trucks path planner.

In our world, there is a strong necessity of developing such “clever” industries. We have an awesome financial, transport, information, energy, healthcare, military, industrial, communication, entertainment and other infrastructures, and their requirements increase in time very fast. Compliance with this requirements means rising of complexity and rising of complexity means significant rising of difficulty of management. At this situation, humans have no chance to deal with such amount of information they need to consider for control in adequate time. The only way to keep all this “alive” is to fully automate control at enterprise level via technologies of artificial intelligence.

So, now we are in the phase of the civilization progress, when complexity of our technologies exceeds our abilities. This state was called “the Technological Singularity”. More detailed this conception is described in (1).

1.1. Multi-agent systems

Because of the developments in math, cybernetics, computer science, artificial intelligence and other disciplines we were able to engineer almost all our surroundings, including control systems. One of the widely used decisions to the enterprise level automation control problem is multi-agent systems, what was proposed in (2).

“Multi-agent systems” is a subsection of artificial intelligence and computer science. It studies “intelligent entities”, how to descript them, how they interact with each other’s, how they interact with the environment, how they decide, plan, cooperate and coordinate with each other’s to achieve their own and the entire system goals.

Well, let's see what the agent is. The concept “agent”, or software agent, is often occurs in many different technologies and is widely used. But no one exact definition of an agent exists. All existing formulations agree that an agent is some unique autonomous program that interacts with its environment and other agents according to its own goals. We can suppose that an agent system can contains only one agent and theoretically it will be correct multi-agent system, but in practice they often consist of multiple agents. Such multi-agent systems (MAS) can model very complex systems with intersecting or conflicting goals of its agents. Agents can[1] interact with each other via communication or direct actions or with the environment around them by acting on it. Agents may achieve some goals by cooperating into groups, may work on their own interests or may help another agent with its goal.

An agent is fully autonomous entity, because it can live without any interaction with humans or other agents, knows about its internal states and has full control on them. But, an agent is also a social entity, because it can cooperate and coordinate with others to achieve its (or their) goals. An agent is reactive entity - it senses the environment it’s live in, analyzes what happened and

[1] From our point of view, they must, otherwise one of the main purposes of multi-agent system is lost.

realizes the appropriate response. Finally, an agent is proactive entity, because it has its unique behavior based on its and goals and prioritization mechanism.

Moreover, is often needed that an agent be mobile, because multi-agent systems are widely used in some kind of networks that require ability to move between different nodes (explained in detail in (3)).

1.2. Real applications of agent technology

Multi-agent systems are widely used in a huge number of different applications, ranging from relatively small embedded systems to large mission critical distributed over the Earth applications.

Industrial applications were the first, where the potential of multi-agent system technology was verified and demonstrated. Generally, it is mainly because of industries are strongly interested in technologies that could increase production line reliability and effectiveness. Examples of such applications are: system control and maintenance, diagnostics, manufacturing, transportation logistics, network management, tactical simulation, distributed planning and so on.

In the information century data management looks like one of the most important application fields of multi-agent systems. Internet is a very “interesting” environment for agents as it has unbelievable huge amount of information and a native distributed structure. Agents can search and filter this mass of information, balance loading on the particular segments, for example DNS can be fully realized via multi-agent technology, monitor the entire Internet from economical or security positions and more and more. As shown in (4) the Internet is also a very developed commercial field where agent technology can find its role. Is a fact, that before the spread of Internet commerce, business was almost entirely managed by humans. Humans were deciding what and how much to produce, when to buy goods, how much they were willing to pay, and so on. Nowadays, e-commerce and business intelligence offer opportunities to significantly improve the way in which the different entities involved to the business process. Under such conditions multi-agent systems look like to be both suitable for the modeling and the managing of business processes.

Traffic, road balancing and transportation networks is also very important field. The traffic has distributed nature and strong independence among the participants. It makes multi-agent systems a good tool for realizing effective commercial solutions. As an example, look at the Sydney airport, where traffic is controlled by multi-agent system called OASIS (see (5)). This fact provides strong argument that multi-agent systems are good applicable for open, complex, mission-critical systems.

Telecommunication is another field of the successfully application of multi-agent systems. Telecommunication systems are very large, distributed networks of interconnected devices which must be monitored and managed permanently to ensure its correct functionality and to provide the competitive basis on the market where telecommunication companies and service providers try to distinguish themselves from their competitors by providing better, quicker and more reliable services. Because of that, multi-agent systems are used here both for the management of such distributed networks and for some advanced telecommunication services like P2P networks. An interesting example of P2P approach in multi-agent systems id described in (6).

1.3. Markets of electrical energy

Electrical energy is a physical product – the flow of electrons. It is a secondary energy source in essence, that it gains as a result from the conversion of other type energy forms such as natural gas, coal or oil, or the inner energy of wind, sunshine or the flow of water.

Energy markets include two other submarkets: retail and wholesale. Retail markets directly sale electricity to consumers; wholesale markets typically sale electricity to electric utilities (like distribution stations) and electricity traders before it is finally sold to consumers via retail markets.

Almost all wholesale markets and some retail markets are competitive in the sense that prices set during competition. Other prices are determined by the service provider's cost of service. Because of the tense competition on the energy markets, prices reflect the factors which affect energy supply and demand. Supply includes energy generation and transmission. It must be adequate to satisfy all customers demand simultaneously, instantaneously and reliably.

As described above, key supply factors affect resulting prices. For clarity – there is some examples of these factors: fuel price, capital cost, power lines characteristics and constraints and the operating characteristics of power plants. Extremely high levels of demand can affect prices as well, especially if less-efficient, more-expensive power plants must be exploited.

In the Czech Republic and other developed countries, electricity is expected to be available whenever people need it. The electrical demand has grown significantly as consumers today consider not only refrigerators, TVs and hair dryers but also computers, iPods and other electronic devices as necessities. Consumers also expect to pay reasonable prices for the electricity they use.

Satisfying these customer expectations and requirements is challenging. Unfortunately, electrical energy cannot be stored (with few exceptions) in any appreciable quantities. Consequently it must be produced as needed. In difference from most other markets, the electrical one has historically inelastic demand. To provide electricity on demand, the entire electric system must in detail plan its activities. Lacking "warehousing" and responsive demand, operators must carefully plan and operate power plants and the transmission grid to achieve the expected level of supply every moment of the day, every day of the year, in every location. Energy markets is described in (7) more detailed.

2. Energy grids

We will begin with the short historical introduction to the world of energy networks.

In the last century, power communities were rather small, but they grew over time fast and during their growth they were little by little interconnected into larger grids. In the 60s, energy networks of all countries, where economics grew significantly, had become very massive. They had consisted of thousands “main” power plants delivering energy to appropriate load centers via high capacity power lines. Later, these lines were split to provide energy to industrial and domestic communities which were located far distant from the “main” supply area. Emergence of grids with such topology is explained by the fact, that there were a lot of large fuel-fired power plants (coal, gas or oil) – the superior generation technology of that time.

Thermal power plants were built on strategically “correct” positions. They had to be close fuel depots or either to mines/wells. Also a reasonable location was near some supply lines (road, rail, ship). Nuclear power plants were located close to large lakes or other water reservoir as they require a lot of water for cooling. On the beginning, thermal power plants were very dirty and, because of it, they were placed as far from towns, as it was economically possible. To the end of 60s this grid had covered almost all territory of their countries.

Next 20 years, from 70s to 90s, growing energy demand provoked an increasing the number of power plants. There were emerged areas, where at times of peak loading power plant could not satisfy the demand. Aftermaths were expected: poor power quality, power surges, power cuts and so on.

At the end of the 20th century the reason of the demand peaks was found by the statistical analysis of the demand – it was heating and air cooling. So the decision was simple, were built some “peaking power plants” that would only generated energy at the moment of peak loading. Generally as peaking generators were used gas turbines, because they had rather low capital cost and were fast to start. This complexity were resulted in higher operating costs, and consequently, higher tariffs.

2.1. Smart grids

As we discussed above, humanity strongly needs to develop and implement technologies of autonomous control at enterprise level for almost all types of industries we build. This paper focuses on a solution, which was developed and successfully verified in practice for the control of electricity network. It is a new generation electrical grid - smart grid (see Figure 1).

Under the term “smart grid” we will understand some relatively small, enclosed community of energy generators and consumers. It has the ability to intelligently adapt to the situation on the energy grid (actual loading of power plants, weather condition and so on) and on the grid market (current electrical demand, price for energy at the moment, etc.) including generation optimization and distribution, resulting energy price changing, power lines balancing and planning its activity for the future (8).

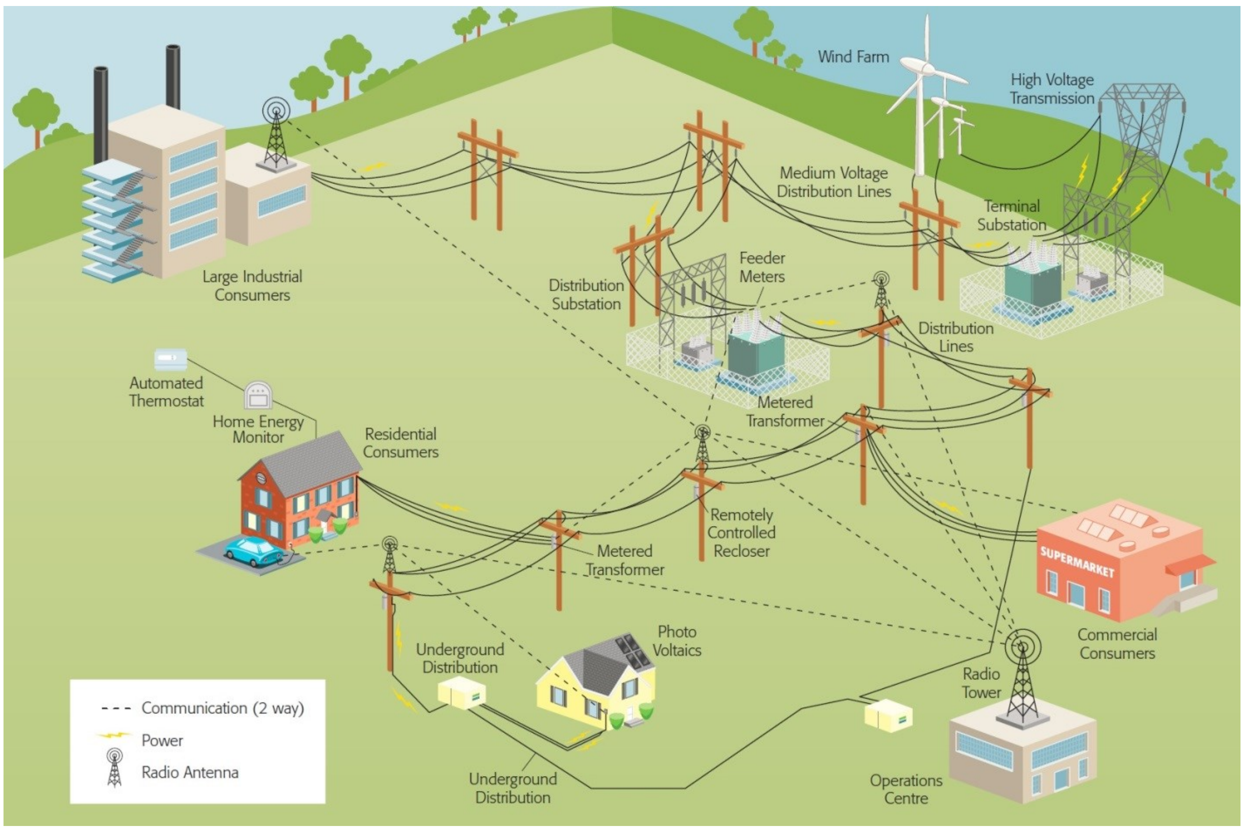

Figure 1 Visualization of the smart grid (source: http://www.eco.on.ca/blog/wp-content/uploads/2011/07/Tomorrows-smart-grid.jpg)

2.1. Smart grid features and characteristics

The smart grid technology provides a rich set of features that can response to the challenges of electricity supply. Here, we will try to describe the most eminent properties of smart grids.

Reliability

The smart grid is intensively using the artificial intelligence technologies to automate its processes. It reduces the probability of wrong diagnostic and allows self-healing of the grid without any actions from humans. It enhances reliability of supply in the entire community.

Topological flexibility

Smart grids use next-generation energy distribution technologies which enable to transfer energy in both directions simultaneously. Bidirectional energy transmission makes it possible to use fuel cells, small photovoltaic panels on roofs, hydroelectric pumps or even batteries of electric cars in the smart grid. Such grid could have unpredictable topology, but it still be optimal.

Efficiency

Smart grids have advanced consumer-side management. It allows, for example, automatically turning off the charging of the electrical car during the demand peaks period, what will reduce both costs of the consumer and load of power lines. The result is less wear of energy distribution lines and better utilization of generation turbines.

Load adjustment

At different moments there can be connected to the power grid a large number of devices, so energy demand can greatly differ over the time. As the total consumption at the moment is a sum of individual consumer's requests, on the grid level energy demand is not stable and is varying. Imagine, how the energy grid load will increase if a popular TV show will begin and a lot of televisions will be turned on in the same time. To solve this situation, smart grid can send a warning message to the appropriate clients to reduce their consumption for a while, until some large generator starts or to inform about generation limit is reached and consequently significant increased price for energy.

Market enabling

One of the direct features of smart grids is ability to dynamically change the price for energy according to the situation on the market. It is achieved by the communication between suppliers and consumers during the establishing the price for the current moment. Each consumer and power plant determines its requirements and creates the plan how to fulfill them. So, all participants of the market specify their operational strategies independently on each other's. Power plants, which are more flexible in their price strategies, will be able to get a higher profit, than less flexible generators. The last ones will receive a changing demand prices according to the actual level of consumption and state of other power plants.

Platform for advanced services

Smart grid is a suite of next-generation technologies based on artificial intelligence, cybernetics and math. It uses advanced sensors, bidirectional communications and energy transmission, predicting of its future states, distributed computing and other science achievements. Together, all this features creates a good basis for entirely new services which could be built on it. For example, smart grid can provide automatic fire protection by monitoring the area in houses via the fire/smoke sensors and make phone calls to emergency services.

3. Problem description

As we have seen, smart grids is a perfect promising technology which will replace traditional electric networks, both generation and distribution. Because of the fact, that smart grids can be used instead of energy networks of almost all sizes, in this work we will focus on a small smart grids. Small is a relative concept, so let's describe what it means exactly.

3.1. Considered environment

The smart grid, which we will analyze, might be not very large, because we will simulate its behavior in a real time and we have strongly limited computational resources (just one PC). For example, consider a small town, 2-3 small generators and about 15 civil buildings (resident buildings, shops, some town infrastructure objects like warehouses, fueling stations, mail, commercial offices, schools and other). As we are simulating the energy network of the future, we will prefer renewable energy sources, i.e. solar or wind. Both wind and solar power plants are strongly depend on current weather and consequently they are not stable in their supply function, but we can predict their production according to the actual weather forecast. The energy demands of civil buildings depend on weather too. For example, the heating requests are closely connected to the outside temperature. Of course, our town will have connection to the state main energy network, but energy bought from the external grid will be much more expensive. This is done purposely, because our goal is to simulate enclosed community, so all objects in the town will be forces to prefer local suppliers.

3.1.1 Wind power plant

One of the most common alternative energy sources is a wind (9). So we cannot avoid simulating wind power plant (see Figure 2) it in our fictional smart grid. For simplicity we will not simulate the entire physics behind the generation process and will simplify it with the following representation: wind power plant is an electrical energy generator with specific maximal output, but its real output depends on the current intensity of the wind. As any commercial organization, power plant needs to sell its product; consequently it has some minimal bound for the price to the kilowatt/hour unit. Next we will use the term profitability bound as a synonym. We will consider it as a constant, as its emergence is out of this thesis focus. Selling energy for a minimal price isn't a goal in any cases, it is only a survive constraint.

Each power plant is mainly interesting to sell energy as expensive as it's possible. It's also has a price coefficient which defines the value of offer price reduction at each step of the trading. Power plant starts the trading with the $p = p_{\min} \cdot c$ price value, where $p_{\min}$ is a profitability bound and c is a price coefficient. If the trading was unsuccessful at this level of price, power plant reduces it by subtracting the $10/c$ value, so the new offer price will be $p_{new} = p - 10/c$. If $p_{new} \le p_{\min}$ the trading proceeds with the $p_{\min}$ value offered.

Figure 2 Example of wind power plant (Source: http://upload.wikimedia.org/wikipedia/commons/e/e0/Wind_power_plants_in_Xinjiang,_China.jpg)

3.1.1. Solar power plant

The next common (in our fiction smart grid) power plant is a solar power plant (see Figure 3). The generation process and all physical background are perfectly described in (10). Solar power plant is conceptually equaled to the wind one. It has the same motivation, similar behavior on the market and the same list of parameters.

Figure 3 Rather large photovoltaic panels (Source: http://www.abc.net.au/reslib/201005/r564892_3442636.jpg)

3.1.2. Gas power plant

The last kind of power plant that can be in our smart grid is a gas power plant. As any other thermal power plant, the gas one is stable and predictable as its production sustainability depends only on availability of fuel to burn. The price of energy is not low, because gas is expensive, and running cost of the burning unit is high. Thermal power plants produce rather large pollution. The gas power plant is the cleanest one among the thermal plants, but with comparison to solar or wind, it is still dirty and not preferable to appear in the smart grid of the future. We will try to minimize the consumer's attention paid to gas power plants in our simulation and will have such setting, in which gas-based energy will be the most expensive (exclude energy from the external network). It means, that consumers will buy its energy only if there will be no other offers. For more information about gas power plants, see (11).

3.2. The energy exchange

Power plants need to sell their produced energy, all other members of our smart grid need to satisfy its energy requirements. As we have described above, smart grid is a kind of “intelligent” energy network. Property “intelligent” in this context means, that it can automatically adjust its behavior according to the dynamically changing situation. In our simulation it will be maximal outputs of power plants, because they depend on weather and, of course, these changes will affect the price for energy. So, we need a mechanism to realize this intelligence. Decision for our smart grid will be based on the exchange trading’s concept:

A virtual object will be also connected to the smart grid, so-called energy exchange. Example of the real Czech energy exchange is shown in (12). Requests for selling or buying energy participants must send to the exchange, not to the power plants or houses directly. The exchange will process all requests and if there will be some realizable pair send a confirmation to the appropriate power plant and consumer.

Energy will sold for hours. I.e. each power plant and consumer can predict (based on weather forecast) its energy requirements for the next hour. During current hour, each member can buy/sell energy for the next hour only.

4. Formalization and solving

Now let's speak more formally and describe our environment and goals precisely. We have a set of power plants, a set of energy consumers and an exchange (is shown on Figure 4). Power plants want to sell energy they produce, consumers want to buy energy they require, and exchange provides the ability to do it to both sides. Power plants update their energy output and consumers update their energy requirements according to the weather forecast.

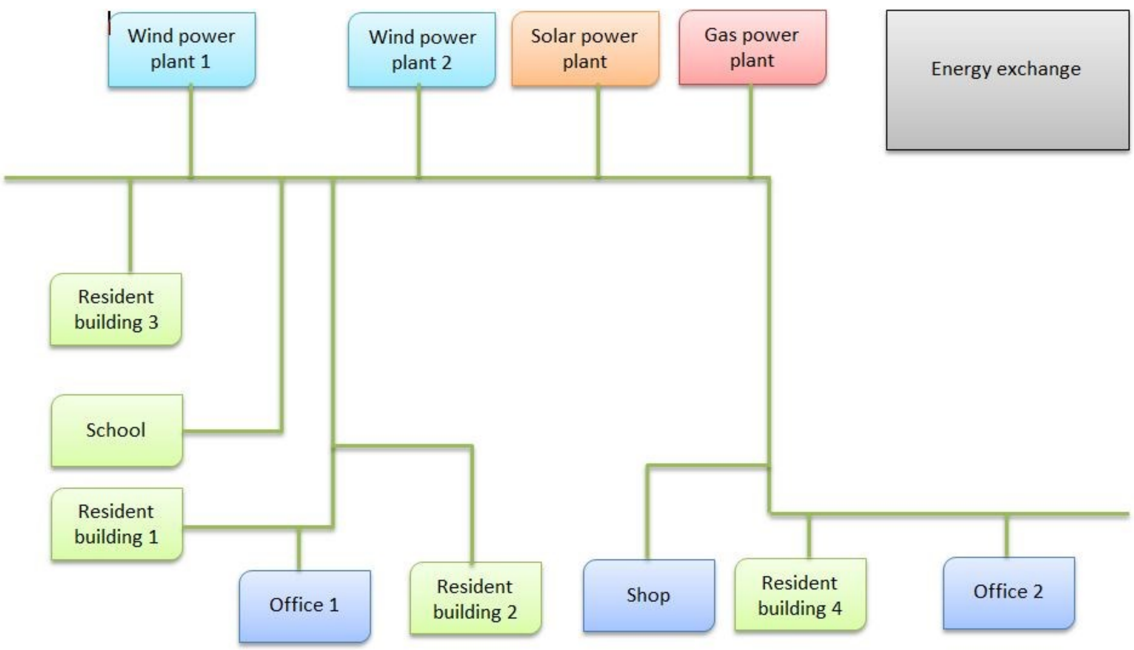

Figure 4 Approximated map of our simulated smart grid might look like this. Green lines represent power line connections

As we can see on the image above, essentially our energy community is a small group of inter-connected by power lines objects. We will not focus on any characteristics of power lines and just assume, they can transmit any energy and without losses.

Now we will describe the smart grid trading algorithm:

1) Power plants adjust their maximal output according to weather forecast, compute the prices (as described in 3.1.1) for energy unit and create a sell requests to send to the exchange; consumers adjust their energy requirements according to weather forecast, compute the prices they will offer for energy unit and create a buy requests to send to the exchange.

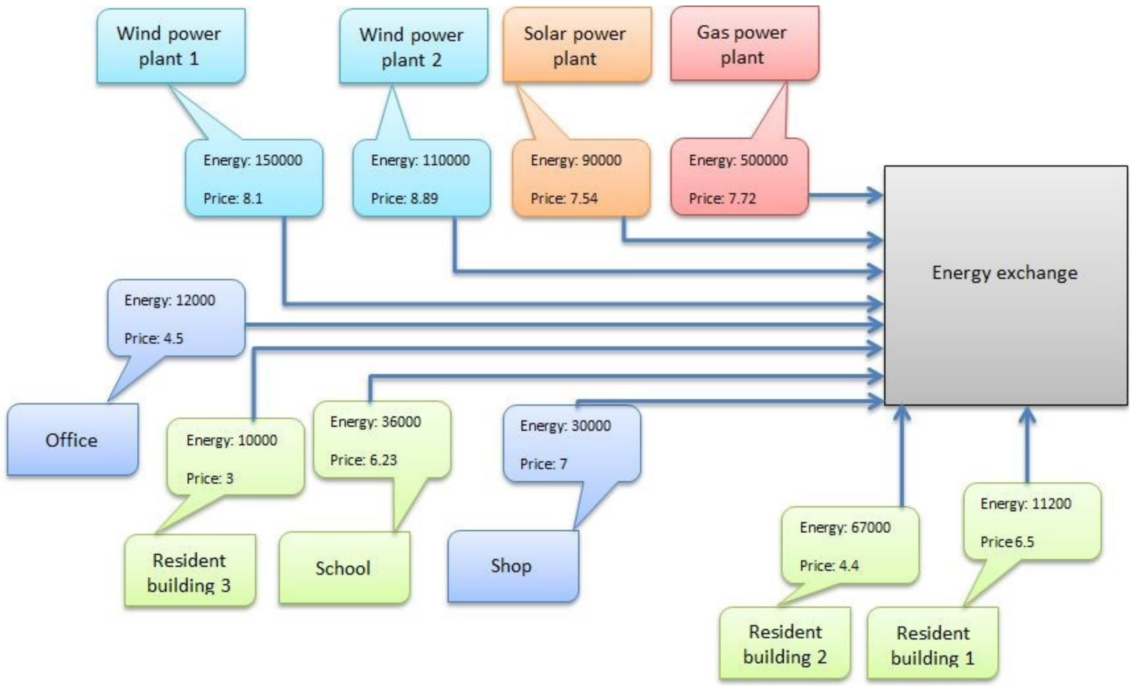

Figure 5 Schematic visualization: power plant and consumers sending their requests to the exchange

2) Both power plants and consumers send their requests to the exchange (see Figure 5).
3) While a new request arrived to the exchange, it immediately places it into appropriate data structure (there is two particular priority queues for sell and buy requests) and launches the trade subroutine.
4) Trade subroutine checks, if there is at least one sell request and at least one buy request, and if yes, removes them from queues and continues with comparison of prices from these requests. If price of buy request is equaled to or larger than the price from the sell request, Exchange closes this deal and sends "OK" messages to the appropriate objects. Otherwise sends the "FAIL" messages. This step is visualized in Figure 5.

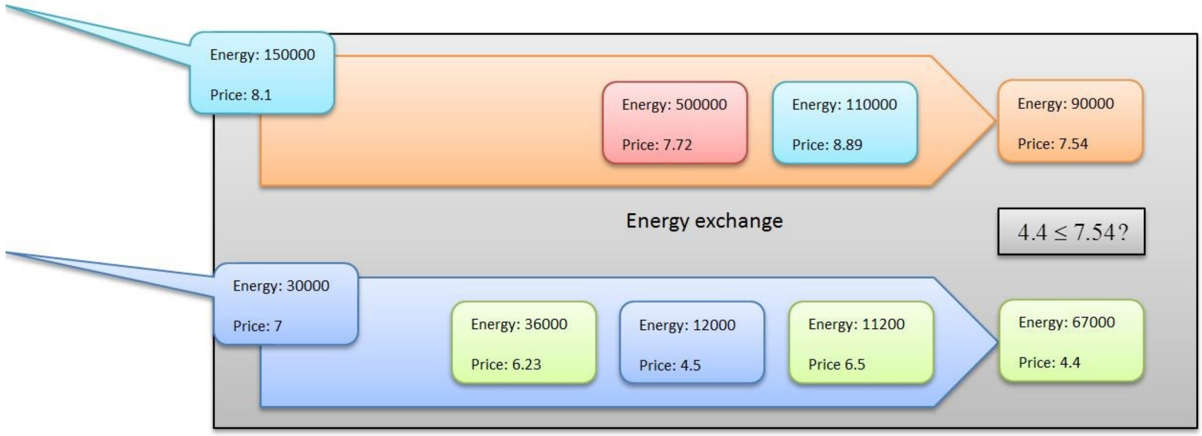

Figure 6 Exchange inner structure visualization. New sell or buy request can arrive anytime and exchange puts it into the correct queue. Once a new request is arrived, the trade subroutine is launched

5) Exchange checks actual time and if a new hour occurs, clears all queues.

Algorithm described above will be executed every hour. For the entire smart grid it means, that electricity will be allocated only for the next hour and then, during it, the trading's for the next to "next" hour will proceed. So, our power plants will sell energy only for an hour and consumers will also buy energy only for an hour and this process will be permanent.

5. Simulation

Now we are ready to launch the simulation and observe how our smart grid looks like, how it behaves and so on. First, let's describe participants: there will be two wind power plants, one gas, one solar and eleven houses. We will simulate unstable weather conditions to look, how our smart grid can adapt to them, because of that there is a gas power plant. It is wittingly made that solar and wind power plants can't generate all required energy every moment, but we make energy from the clean sources much cheaper than from the gas station, and so our houses are motivated to the "correct" decisions. Unfortunately, we cannot simulate a month or even a week because it requires much more computational resources that we have, therefore we will simulate just one day.

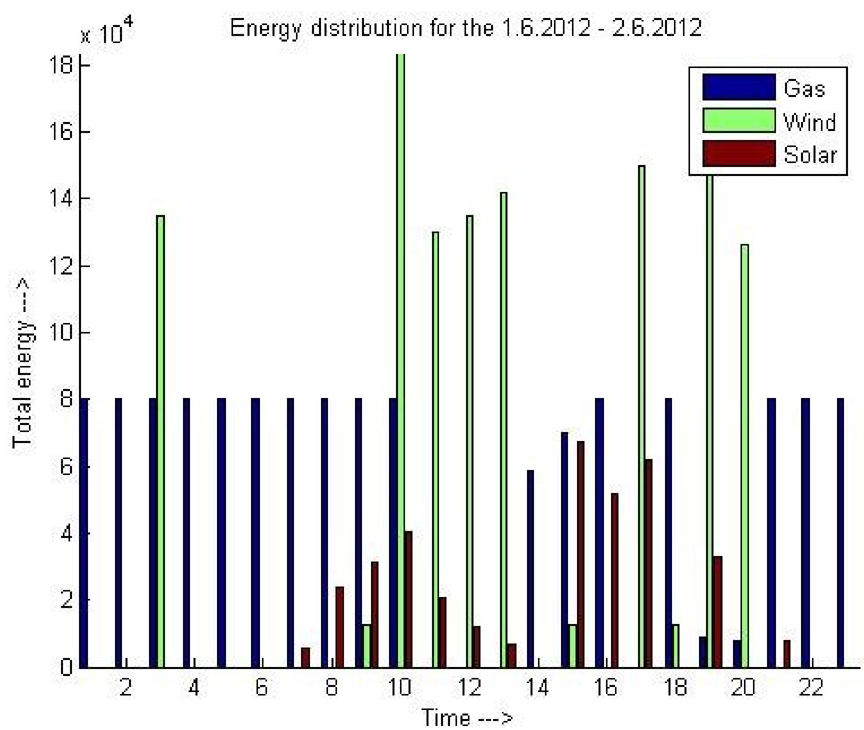

Figure 7 Total energy distribution

Here, on the Figure 7, we can see how energy is distributed across different energy sources satisfying requirements of consumers. Notice, that according to weather conditions, it can be sunny or cloudy, windy or windless. It directly affects the amount of wind or solar energy generating in the grid. Let's see how the wind was being changed during the simulation period.

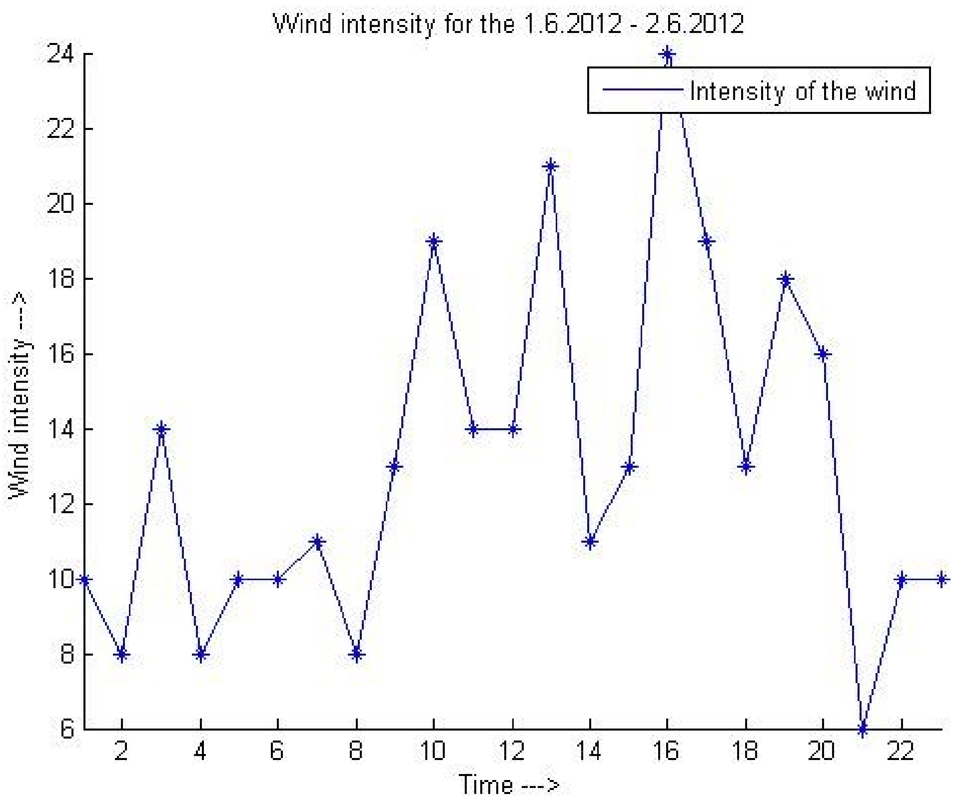

Figure 8 Wind intensity graph

According to the Figure 8, on the peak values of wind intensity we can observe an involvement of wind power plants to the generation process. The alone gas power plant cannot produce the amount of energy houses require, because of that, in the hours when it's windless and cloudy (no other sources than gas are available) some houses has no energy, because there isn't on the market.

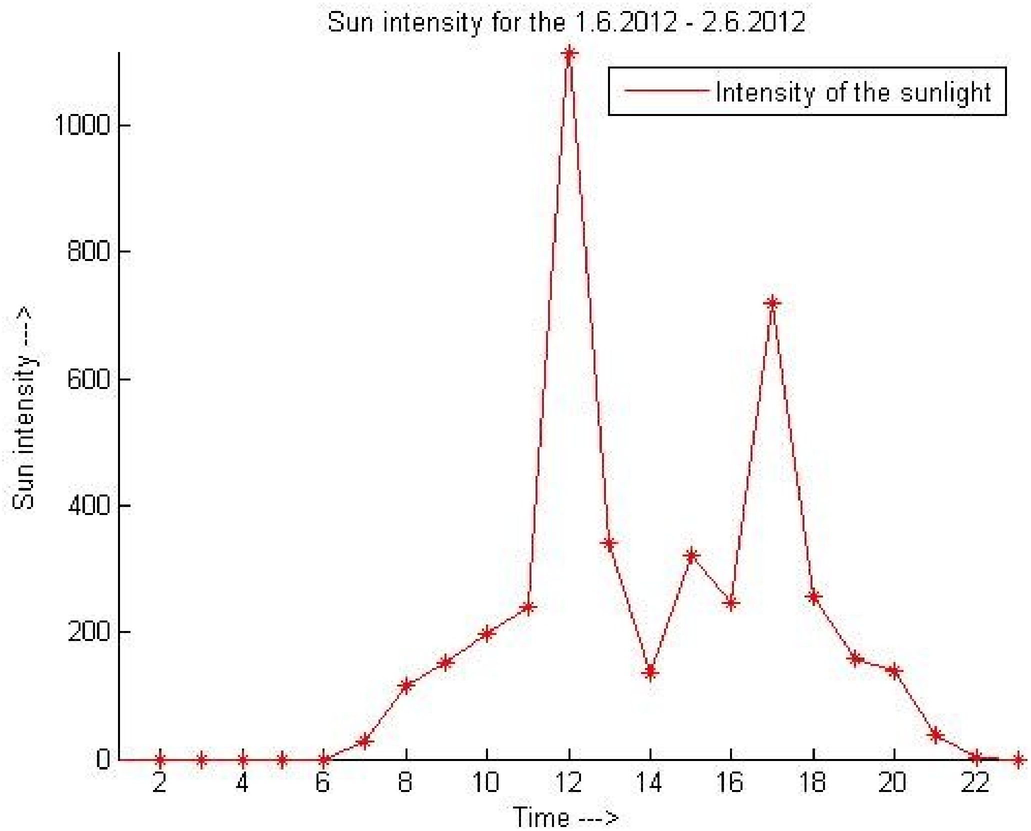

Figure 9 Sun radiation intensity graph

With the intensity of the sun we see another situation: not on every peak value of sun intensity the solar power plant can sell large amount of energy. Houses set their preferences according to the price of energy and the solar based one isn't the cheapest[2]. Sun radiation graph is shown on Figure 9.

Generally, when there is a choice between the wind/solar based energy and the gas based one, consumers obviously prefer clear sources, and this is an expected behavior.

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[2] A reader may expect to see a high amount of energy from the solar power plant at the 12th hour (because there is a highest value of sun intensity) and can suggest that is something wrong, because the 12th hour requirements is almost satisfied by the wind plants and only a little by the solar. First, we make a very small solar generator in our simulation, and second – it is simply more expensive, than the wind ones.

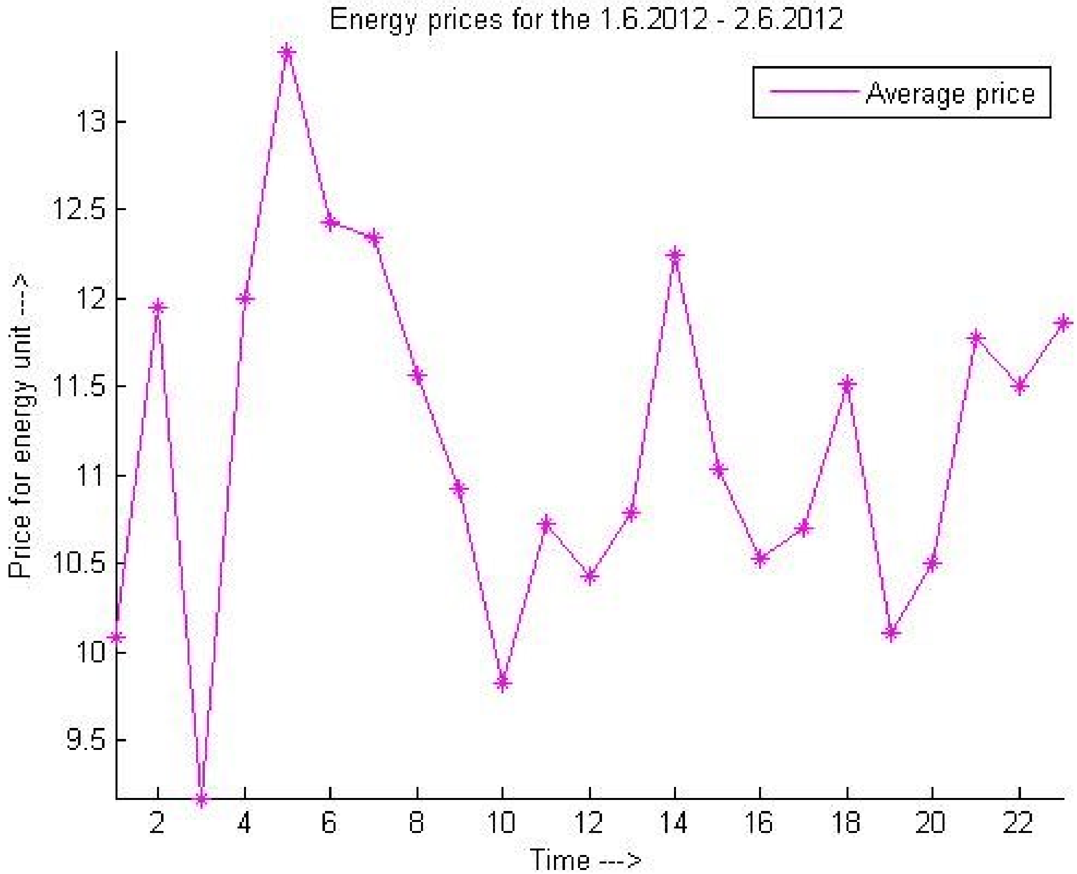

Figure 10 Values of average price for the energy unit at an each hour

A price value is computed as the mean of prices from all deals at an each hour (see Figure 10). The amount of energy from every deal is also taken into account.

If we compare this graph with the energy distribution we can immediately observe interrelation between the type of energy source that prevails on the market at the moment and the value of average price for the energy unit. For example look to the first two hours. There was bought the same amount of gas based energy. The difference between values (~10 and ~12) of average price is explained by the fact that buyers could be different, with different ability to pay. Also is interesting the 10th hour – there was the largest energy demand of the day (is simply obvious by lengths of bars from the graph) and all power plants were loaded at the maximum[3].

[3] A reader may consider that at 15 o'clock there was more solar based energy than at a 10 o'clock. In that fact a reader must also consider the difference between sun intensities at 15 o'clock and 10 o'clock.

6. Implementation notes

Let's shortly describe the inner structure of the simulation program and eventually argument our decisions.

We choose the Java platform[4] as the main framework to build our solution. Java is cross-platform, has a lot of open-source external libraries and its usage is completely free. More about Java, reader can find in (13). So for our purposes Java looked like a best choice.

Next, we needed a multi-agent platform, because multi-agent technology is the best method to simulate behavior of such system (See 1.1). We found JADE[5] framework the most appropriate solution, because it is free, simple and it has very good documentation[6]. For more information about JADE framework and development under it, see (3).

Software is divided into 2 layers – a control layer and a world layer. World layer simulates physical processes like time, weather, buildings hardware properties (including power plants and residential buildings) and it determines their requirements. World layer is out of our focus in this paper. Control layer simulates trading's and all objects of our smart grid with their high-level behavior (See 3.1). It communicates with the world layer to get the needed information, like weather condition or actual states of objects, than it simulates trading and message the world layer about changes (for example, how much energy has sold each power plant to the next house).

Now we will quickly describe the classes it consists of:

Configuration

This class contains all functionality to read and parse an XML configuration file. This file contains all settings of each object in the smart grid. Configuration class contains several nested classes: WindPowerPlantInfo, SolarPowerPlantInfo, GasPowerPlantInfo and HouseInfo. As their

[4] For more information about Java, see, for example, http://en.wikipedia.org/wiki/Java_(programming_language)
[5] To get more information about JADE, see http://jade.tilab.com/
[6] For example, look at the http://www.amazon.com/Developing-Multi-Agent-Systems-Wiley-Technology/dp/0470057475

names imply, this nested classes are essentially containers of settings for the building of appropriate type. Configuration class parses XML file, for each building and creates corresponding Info object.

EXCHANGE

This class contains the logic of energy exchange (See 3.2). First of all it is a JADE agent. It also has some nested classes: HouseEntryComparator, PowerPlantEntryComparator and ExchangeEntry. ExchangeEntry is a convenient representation of trade requests; it simply contains information fields about its sender, energy requirement and offered price; HouseEntryComparator and PowerPlantEntryComparator are realizations of the Comparator<ExchangeEntry> interface. Their difference is that for the PowerPlantEntryComparator the largest entry has the largest price and for the HouseEntryComparator it is contrariwise.

Then, Exchange has two priority queues for arrived trade requests: sell requests (from power plants) and buy requests (from energy consumers). Once a new request arrives, Exchange puts it into the appropriate queue and calls the exchangeProceed() method to provide the trading. Also Exchange listens to the time from the world layer. It's realized via the Observer pattern, so Exchange has an update() method which processes it. Because, on the occurrence of the new hour Exchange must clear all requests, both priority queues are also thread-safe.

IEN

This is the application entry point. This agent starts immediately after JADE platform initiates. It's the only goal is the simultaneous start of all other agents. First it reads the XML configuration file via the Configuration class and creates instances of all objects. Next it waits the confirmation from launched agents that they are ready. After all confirmations received, IEN send a start signal to all objects and a world layer to start simulation.

GASPOWERPLANT, SOLARPOWERPLANT, WINDPOWERPLANT, HOUSE

The names of these agents should speak for themselves. They contain smart-grid behavior logic of the appropriate objects. They are very similar. Each of them has a list of fields to write parameters to from the received Info object. Each of these objects starts, confirm its readiness by sending a message to the IEN agent and waits for a signal to begin trading's. Then they simple ask the world layer about their energy requirements, compute offer prices, send them to the Exchange and wait for the answer. This loop ends only with the end of the entire simulation.

LogEntry

It is a class for the log of successful deals. It contains a seller field, a buyer field, a field for the amount of energy, a field for the price and a field for the time sample. Essentially, it is just information object.

7. Conclusion

The goal of this work was to find principles and technologies that are used to build new generation energy networks, develop a program that able us to simulate a simple smart grid in a real time and analyze the results of simulation.

We provide an introduction to the entire situation, describe, why it is important to develop smart grids, we explain current situation in the energy world and show what will change because of this technology and why. Then we simulate a small enclosed community. The results of simulation confirm our assumptions.

Simulation has shown a set of dependencies between initial settings of smart grid participants and their behavior during the energy trading. The very important note was about impact of the prevailed power plant type on the resulting price. We supposed the gas power plant to be the most expensive (with reason to motivate consumers to buy energy from the cleaner generators), on the second place there was solar-based energy and the cheapest one was the energy generated by wind power plants. Maximal outputs of power plant were rather small; this was done intentionally and allowed us to observe, which type of energy was chosen as the second preference, under current conditions. About a half of simulation time there were only two types of energy (or, even only one) on the market, because wind and solar generators are strongly dependent on actual weather conditions. Often, even two different sources of energy on the market could not produce the required amount of energy, and it results in higher prices. Generally, under such strict simulation conditions trading with individual consumers were often ended on the price value near consumers maximal value its able to pay. Nevertheless, we have seen a tense competition between power plants in their pursuit to sell energy.

Then we try to simulate the same smart grid with significant increased maximal outputs of all power plants, what was meant, that any one power plant could produce the expected amount of energy every moment, except weather-based constraints. We expected that consumers would prefer energy from solar station, as it was sunny.

Possible improvements of this work could include, for example, migrating the simulation core to the A-globe multi-agent platform or optimizing the agents messaging loop to increase performance. Also a good addition could be an automatic generator of smart grids to simulate, because in this version configuration file was created by hands.

8. CD content

The attached CD contains this work in the PDF and MS Word 2010 format. It’s also contains a *JAVAsrc* folder with the source code in the Java language. All needed libraries are in the *JA-VAsrc\lib* folder.

Bibliography

1. **Vinge, Vernor.** The Coming Technological Singularity. *SDSU Faculty Home Pages.* [Online] 1993. http://www-rohan.sdsu.edu/faculty/vinge/misc/singularity.html.

2. **Rosenschein, Jeffrey S. and Stone, Peter.** *Autonomous Agents and Multi-Agent Systems.* s.l. : Springer US, 2013. 1573-7454.

3. **Fabio Luigi Bellifemine, Giovanni Caire, Dominic Greenwood.** *Developing Multi-Agent Systems with JADE.* s.l. : Wiley, 2007. 978-0470057476.

4. **Ramonaite A., Hutzler G.** Multi-agent System forInternet acceleration. *Laboratoire IBISC.* [Online] 2002. http://www.ibisc.univ-evry.fr/~hutzler/Documents/STAIRS02.pdf.

5. OASIS (Optimal Aircraft Sequencing using Intelligent Scheduling). [Online] http://www.stern.nyu.edu/om/faculty/pinedo/book2/downloads/CMU-Salman/Reference%20Articles/oasis%20aircraft%20sequencing.html.

6. **Dimakopoulos, Vassilios V. and Pitoura, Evaggelia.** A Peer-to-Peer Approach to Resource Discovery. [Online] http://www.cs.uoi.gr/~pitoura/distribution/cia03.pdf.

7. A Handbook of Energy Market Basics. *FERC.* [Online] July 2012. http://www.ferc.gov/market-oversight/guide/energy-primer.pdf.

8. **Hicks, Christian.** *The Erb Institute.* [Online] 2012. http://erb.umich.edu/Research/InstituteReports/11-12/Hicks-Smart-Grid.pdf.

9. Information about wind energy industry. *CEZ Group.* [Online] http://www.cez.cz/en/power-plants-and-environment/wind-power-plant/basic-information.html.

10. **Boxwell, Michael.** *A Simple Practical Guide to Solar Energy - Designing and Installing Photovoltaic Solar Electric Systems.* s.l. : Greenstream, 2013. 978-1907670282.

11. **Boyce, Meherwan P.** *Gas Turbine Engineering Handbook, Fourth Edition.* 2011. 978-0123838421.

12. *POWER EXCHANGE CENTRAL EUROPE (PXE): About.* [Online] 2013. http://www.pxe.cz/dokument.aspx?k=Co-Je-PXE.

13. **Darwin, Ian F.** *Java Cookbook, Second Edition.* s.l. : O'Reilly, 2004. 0-596-00701-9.