Chapter 1

SADDE: SOCIAL AGENTS DESIGN DRIVEN BY EQUATIONS

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Abstract This work explores the existing gap between multi-agent specification and implementation and the potential help that evolutionary programming techniques can bring in. We present a methodology to help the programmer in the transition from a set of desired global properties expressed as an equation-based model that a Multi-Agent System (MAS) must fulfill to an actual society of interacting agents. The evolutionary techniques are seen, within this methodology, as a procedure to tune the parameters of the population of agents in order that their aggregated behaviour maximally approaches the desired global properties.

Keywords: Equation based model, multi-agent system, agent based model, evolutionary computing.

Introduction

A fundamental difference between the ecologist and chemist and the software engineer is that lions, gazelles, atoms and molecules already exist. They are *natural*. Scientist don't need to *design* them. Their task consists on observing phenomena and building a set of equations for which the observed reality is a model. If the predictions of the equations and the reality don't match, the set of equations is wrong. The scientist then refines the equations until predictions and reality match. It works opposite to the methodological approach presented here, as we hope to make clear by the end of it.

The general goal of the research reported here is to better understand the dynamics of large (*artificial*) Multi-Agent Systems with globally distributed and interconnected collections of human, software and hardware systems; each one of which with potentially thousands of components.

To understand these dynamics we take a different stance than the traditional *emergent behaviour* community. We focus our attention on the study of the relationships between the *a priory* desired global behaviour of an agent society and the actual emergent behaviour shown by the group of agents forming the society. In a sense, we feel that in order to have a handle into the engineering of complex systems we have to first specify the desired behaviour and second find ways to restrict the potential complex interactions among agents in order to foresee an emergent behaviour that does not depart substantially from what is expected. Within this ambitious goal we present a methodology based on three main ideas. First, a particular approach to the principled design of MAS using Equation-Based Models (EBM, for short) as a high level specification method, where equations model the aggregated behaviour of the agent populations abstracting from the interaction details of individual agents. Second, the use of *Electronic Institutions*, as the way to restrict the interaction among agents in order to be able to *engineer* the emergence. Third, the use of evolutionary computation techniques to find out what agent structures produce the behaviour specified in the EBM. These ideas frame our design methodology called SADDE (Social Agents Design Driven by Equations).

1. The SADDE Methodology

We take the stance that in order to build a model for a society containing thousands of agents, the general view provided by an EBM provides succinct descriptions of population-level behaviours which we then attempt to replicate using models consisting of a society of individual interacting agents. Our proposed lifecycle is graphically depicted in Figure 1.1.

An important characteristic of MASs design from a software engineering perspective is the decoupling of the interaction process between agents from the deliberative/reactive activity within each agent, [1, 8]. The notion of *electronic institution* [2, 4] plays this role in our methodology by establishing a framework that constraints and enforces the acceptable behaviour of agents.

The different phases within SADDE are:

Step 1 EBM – Equation-Based Model. In this first step, a set of state variables and equations relating them must be identified.

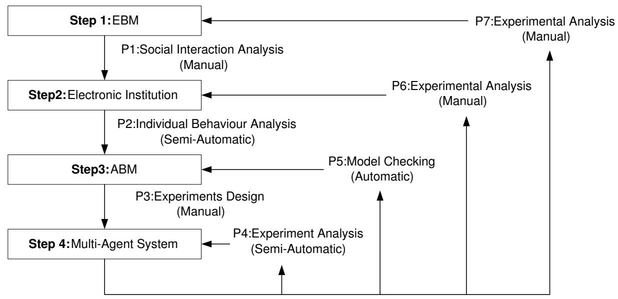

Figure 1.1. SADDE Methodology

These equations have to model the desired global behaviour of the agent society and will not contain references to individuals of that society. Typically these variables will refer to values in the environment and to averages of predictions for observable variables of the agents. The EBM is the starting point of the construction of a system that later on will be observed. Thus, a comparison between the EBM predicted behaviour and the actual ABM behaviour will be obtained.

Step 2 EIM – Electronic Institution Model. In this step the interactions among agents are the focus. It is a first "zoom in" of the methodology from the global view towards the individual models. This step is not a refinement of the EBM but the design of a set of social interaction norms that are consistent with the relations established in Step 1. The EBM does not necessarily reflect by itself the set of agent roles that might generate the relations between the global variables. It is the task of the engineer to determine which roles will be present at the level of the society design by means of an electronic institution.

Electronic Institution restrict the interaction between agents in several ways: enforcing protocols (when an to whom say what), restricting movements of agents among activities (scenes) and by enforcing norms that restrict the actions of agents. This restrictions permit to engineer emergence to a certain level in the sense that agents are not completely free to act.

Step 3 ABM – Agent-Based Model. Here, we focus in the individual. We have to decide what decision models to use. This is the second "zoom in" of the methodology. New elements of the requirement analysis (new variables) will be taken into account here. For instance, some rationality principles associated to agents (*e.g.*

producers do not sell below production costs), or negotiation models to be used (*e.g.* as those proposed in [7]) have to be selected.

Step 4 Multi-Agent System. Finally, the last step of our methodology consists on the design of experiments for the interaction of large numbers of agents designed in the previous step. For each type of agent the number of individuals and the concrete setting for the parameters will be the matter of decision here. The results of these experiments will determine whether the requirements of the artificial society so constructed have been consistently interpreted throughout the methodology and thus whether the expected results according to the EBM are confirmed or not.

Once the experiments designed at Step 4 are run and analysed, several redesigns are possible as shown schematically in figure 1.1. The different forward and backward processes of the methodology are:

P1 Social Interaction Analysis. Once the EBM has been constructed, the relations between the global variables and the analysis of the requirements of the society to model will determine what sort of agents exist (*i.e.* the roles), what sort of interactions the agents must have (*i.e.* the scenes), and what sort of transactions or dialogs they will have (*i.e.* ontology). This is an inherently manual process: there are many decisions to be made at this stage that have not been specified in the EBM.

P2 Individual Behaviour Analysis. Once a complete picture of the institution is ready, the final aspect to consider is the modeling of the behaviour of the agents. Many aspects of this behaviour are already determined by the institution. For those aspects that are not completely determined the methodology strongly encourages the design of parametric decision models to fill in the gaps. These parameters will be used to set different experiments and will be the target of agent design rules.

P3 Experiment Design. By choosing agents to participate with (possibly) different decision mechanisms, and by giving concrete values to the parameters of those decision mechanisms, different experiments can be constructed. The experiments should be set so as to explore all the possibilities and to see whether the EBM is making the right prognosis.

P4 Experiment Analysis (ABM redesign). The analysis of the experiments will be done by comparing the predicted values of the global variables by the EBM and the actual values of agent variables and their averages.

P5 Model Checking. The claims about the behaviour of a group of agents that the developer establishes when specifying an experiment will be model-checked at this stage. The outcome of the model checking will help to change the agent-based models, *i.e.* change the decision-making models.

P6 Experiment Analysis (EI redesign). Additionally, when the model checking determines that certain properties can never be guaranteed or that after several trials it is impossible to find parameter values that lead to the expected correct behaviour, different constraints over the agents interactions could be explored. This means that a redesign of the EI may be in place. This is an intrinsically manual task.

P7 Experiment Analysis (EBM redesign). Finally, and if everything fails, it may happen that the part of the requirements that led to the initial EBM was misunderstood and that a variation in the initial EBM is necessary to explain why the experiments are showing unexpected behaviours.

2. A case study: The electricity market

An electricity market is a special kind of market where participants trade with power. It has three main components: producers, consumers and a network that is responsible of distributing the power from producers to consumers. This network has physical restrictions that makes necessary the presence of an external entity, the system operator (SO), that tries to agree the offer and the demand while maintaining the network into the safety operation limits.

Due to this characteristic, an electricity market always has two stages. In the first stage, producers and consumers participate in one (or several) free markets (explicitly forbidden for the system operator) in order to exchange power. After this stage, there is another stage (that is performed just before the power traded in the first stage has to be introduced into the net) where the system operator analyzes the offer and the demand and detects possible problems for the net. If problems are identified, the system operator has several mechanisms to avoid or minimize them as much as possible.

In the following sections we will apply step by step the SADDE methodology to this scenario.

3. Step 1: The EBM

In the EBM we have modelled the three main components of the electricity market: generation, consumption and the electrical network system operator.

3.1 Power generation

The power production has been modelled using three types of power stations: Thermic (coal-fired, gas-fired and fuel-fired), Nuclear and Hydroelectric. The features of these power stations have been taken from the existing ones in the Spanish electrical market during the year 2001. Hydraulic power stations generated a 21% of the global power, Nuclear power stations a 35% and Thermic power stations a 44%. Using these proportions as a reference we can compute the power of each type of power station taking into account that we want to obtain for our scenario a global power around 40000 MW. Concretely in our scenario 9000 MW are generated using hydraulic power stations, 14000 MW using nuclear power stations and 18000 MW using thermic power stations.

In the EBM, we will have a single entity that models the energy production for each type of power station: hydraulic, nuclear and thermic.

Decision modules. Each power generation entity in the EBM (Hydraulic, Nuclear and Thermic) uses a decision module to control the increase or decrease of power production from time t to time $t+1$ taking into account the following criteria:

- The changes of power demand between time $t-2$, $t-1$ and t using the following function:

$$X = \begin{cases} var2 + var4 & \text{IF } var3 > 0 \text{ AND } var2 > 0 \text{ AND } var4 > 0 \\ (var2 + var3)/2 & \text{IF } var2 \leq 0 \text{ AND } var3 > 0 \\ var3/2 & \text{IF } var2 < 0 \text{ AND } var3 \leq \text{ AND } var4 < 0 \\ var2 + var4/2 & \text{IF } var2 \leq \text{ AND } var3 < 0 \text{ AND } var4 > 0 \\ var2 & \text{OTHERWISE} \end{cases}$$

  where *var2* is the increase or decrease of power consumption between $t-1$ and t, *var3* is the increase or decrease of power consumption between $t-2$ and $t-1$ and $var4 = var2 - var3$.

- The performance of a power generation entity at time t (EnergyProd(t)/MaxN) in comparison to the global performance of the system (TotalDemand(t)/41000) with a performance limit of a 70%

$$Y = \begin{cases} \max\left(X, \frac{\text{MaxN}\cdot\text{TotalDemand(t)}}{41000-\text{EnergyProd(t)}}\right) & \text{IF } \left(\frac{\text{TotalDemand(t)}}{41000} > \frac{\text{EnergyProd(t)}}{Max\_N}\right) \\ & \text{AND excess(t)} = 0 \\ X & \text{IF } \frac{\text{EnergyProd(t)}}{MaxN} < 0.7 \\ 0 & \text{IF } X > 0 \text{ AND } \frac{\text{EnergyProd(t)}}{MaxN} \geq 0.7 \\ min(X, 0.7\cdot\text{MaxN} - \text{EnergyProd(t)}) & \text{OTHERWISE} \end{cases}$$

- Every power generation entity have to produce spear energy (Reserve(t+1)) to avoid possible power shortages.

$$Z = \begin{cases} max\left(\frac{\text{Reserve(t+1)}}{3} - \frac{\text{SpearEnergy(t)}}{3}, Y - \frac{\text{SpearEnergy(t)}}{3}\right) & \text{IF SpearEnergy(t) } < 0 \\ Y + \frac{\text{Reserve(t+1)}}{3} - \text{excess(t)} & \text{OTHERWISE} \end{cases}$$

This spear energy production changes during the day following the function:

$$\text{Reserve(t)} = \begin{cases} 3000 & \text{IF } t = 22(mod24) \\ 0 & \text{IF } t = 23(mod24) \\ 1000 & \text{IF } t < 4(mod24) \\ 1500 & \text{OTHERWISE} \end{cases}$$

- The technical features associated to the method used to generate the power.

$$\text{var(t+1)} = \begin{cases} min(Z, \text{MaxI}, \text{MaxN}) & Z > 0 \\ max(Z, \text{MaxD}, 0) & \text{OTHERWISE} \end{cases}$$

where *MaxI* is the maximum power increase per hour and *MaxD* is the maximum power decrease per hour.

Depending on the method used to produce the energy, these constants have the following values:

TYPE of POWER STATION	MaxN	MaxI	MaxD
Hydraulic	9000	5000	-5000
Nuclear	14000	3000	-2000
Thermic	18000	6000	-4000

So, the power produced by a power generation entity at time $t+1$ will be:

$$\text{EnergyProd(t+1)} = \text{EnergyProd(t)} + \text{var(t+1)}$$

Notice that in this decision process we have not used at all the possible future demand of power.

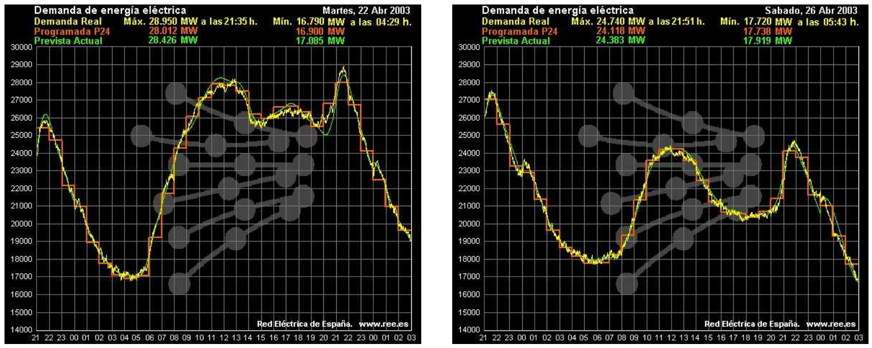

Figure 1.2. Example of demand on a labour day and a Saturday.

3.2 Modelling the demand

The demand has been modelled using as a reference the power consumption in Spain every hour during year 2001. The data has been taken from the "Red Electrica Española" which controls the electrical power distribution in Spain (http://www.ree.es).

It can be observed that power consumption follows four different patterns: labour day, Saturday, Sunday and holidays. For example, figure 1.2 shows the demand on a labour day and on a Saturday,

Using these four patterns we can simulate the demand of energy every hour. The demand for a week is computed using five working days + Saturday + Sunday and we substitute randomly (with a probability of 1/15) one of those days by a holiday.

Once decided which consumption pattern we will follow a specific day, to compute the demand of energy at time t we use the following formula:

$$\text{Demand(t)} = (\text{ConsPattern(t)} + \text{rand}(-250, 250)) \cdot (1 + \sin\left(\frac{\pi \cdot t}{4380}\right) 0.2)$$

where ConsPattern(t) is the consumption at time t given the consumption pattern for that day (ConsPattern), $rand(-250, 250)$ is a uniformly distributed random variable and $(1 + \sin\left(\frac{\pi \cdot t}{4380}\right) 0.2)$ allows us to model the variations in the consumption during the different seasons of the year with a variability over the basic pattern of $\pm 20\%$.

3.3 The electrical network system operator

The system operator mediates between producers and consumers and also has authority to force producers to modify their production in order to satisfy the requirements of quality and security. In the EBM it distributes the demand among the producers using the following sequential procedure:

- If the produced power is less or equal than the demand then the system operator takes all the power production from each power station.

- If the production is bigger than the demand then:

  1 Distributes this demand among producers inverse proportion to the current performance of each power generation entity (where the performance is the ratio between the current production and the maximum capacity of a power generation entity).

  2 If there is still demand to be satisfied, then this demand is distributed in direct proportion to the spear power of each power generation entity.

This method minimizes for each power generation entity the difference between current and maximum capacity of production.

To plan the next step of production the power generation entities take into account the deficit or overproduction of the previous step as was explained in the previous section.

Notice that, in our model, producers decide about their own production and the system operator is responsible only of the demand distribution.

3.4 Power cost

The prize of the power consumed is the total cost of the power produced including overproduction (that is, lost power that has not been consumed).

In the cost of production there is a maintenance cost (that do not depends on the quantity of power produced) plus the cost to produce each unit of power (GenerationCost).

We use Euros for cost and MWh for power production.

Our EBM uses the following costs:

TYPE	Maintenance cost (per hour)	Generation cost (per MWh)
Hydraulic	72000	16
Nuclear	224000	13
Thermic	180000	20

This costs have been obtained using the average cost of electrical power in Spain during year 2002 which is 38.91.

3.5 The EBM in action

The properties that must fulfill the EBM are:

- That the deficit of power be punctual.
- That the deficit of power never be greater than a 10% of the total production, which is the obliged reserve of power that each power generation entity must fulfill.

In the designed EBM, the average cost is 39.16 Euros/MWh that is very close to the real cost (38.91). The power lose (power that is produced but it is not consumed), is less than 8% of the total power consumed and the power deficits are punctual and never greater than 5%. Given these results we can say that the designed EBM fulfills our requirements.

4. Step 2: The electronic institution

The second step in the SADDE methodology consists on the design of an electronic institution that fixes a set of social interaction norms that are consistent with the relations established in Step 1.

The power electricity market we present in this section is based on a New Electricity Trading Arrangements (NETA) proposal presented the October 2000 in the United Kingdom [1].

Roles. There are three roles that an agent can play in the electricity market:

- PRODUCERS: Electricity producers that generate electricity using a different configuration of Power Stations. Power stations are expensive physical plants with a range of physical characteristics and running cost profiles.
- CONSUMERS: large industrial processes and local power distribution utilities.
- SYSTEM OPERATOR (SO): the operator of the energy transmission system, who is responsible for maintaining the supply voltage and system stability (preventing thermal overload and oscillation in flows - dynamic security).

[1] The Spanish protocol is not yet available so we use the English model that is similar to what the Spanish market is expected to be

The Markets. The electricity market is organized, in his turn, in several markets: the primary market, the secondary market and the balancing market. Finally there is a settlement stage.

- PRIMARY MARKET: There are periodic auctions (in our case every hour) of transmission rights, in the form of tickets valid for the injection or extraction of energy for an hour period. The auction protocol has not been specified, although a double auction seems likely. It is explicitly stated that the offer is greater than the demand.

- SECONDARY MARKET: Once the primary market for a specific period has been closed, the arrangements refer to the existence of an unfacilitated secondary market for the trading of transmission tickets. This market lasts until few minutes before the ticket becomes due. This time is known as "gate closure". The objective for consumers and producers is to ensure they hold almost exactly the right number of tickets for each period of time to correspond to planned generation or expected consumption. For this market we propose a one to one negotiation mechanism as the procedure to exchange tickets.

- BALANCING MARKET: This market exists to permit the SO to maintain the voltage level and dynamic security. This market is performed once the secondary market closes. Based on its analysis of the transmission network and the flows as identified by tickets held, the SO can identify shortfalls or excesses of energy that will arise during the ticket window. The actions available to it are: a) to dispatch additional generation. b) to back-off scheduled generation.

- SETTLEMENT: in this stage consumers pay producers for the energy consumed.

These markets should run in parallel, that is, while in the primary market people is buying tickets for period T, in the secondary market they are negotiating tickets for period T' (where T' > T) and so on. However, to simplify, in our scenario we will consider a sequential order. Only one market is open at a time and they are opened sequentially. After the SETTLEMENT stage the cycle starts again with the PRIMARY MARKET.

4.1 ISLANDER specification

An electronic institution model is based on four elements: dialogic framework, scenes, performative structure and norms. The dialogic framework defines the valid illocutions that agents can exchange and which are the participant roles. The institution activity is defined in the performative structure based on the notion of scene. A scene defines a conversation protocol for a group of roles that can be multiply instantiated by different groups of agents playing those roles. Note that all the interactions between participating agents take place within the context of a scene. Thus, a performative structure defines which are the institution scenes (conversations) and how agents, depending on their role and their past actions, can move among them. Finally, norms define the consequences that agents' actions within scenes will have in the future, expressed as obligations.

To illustrate how the electronic institution for the electricity market can be specified using ISLANDER we will show the scene that corresponds to the secondary market. In addition to that, the performative structure of the institution has a scene for the primary market, a scene for the balancing market and two more scenes (the root and the output scenes) that allow agents enter and leave the institution. Figure 1.3 shows a graphical representation using ISLANDER of the secondary market scene.

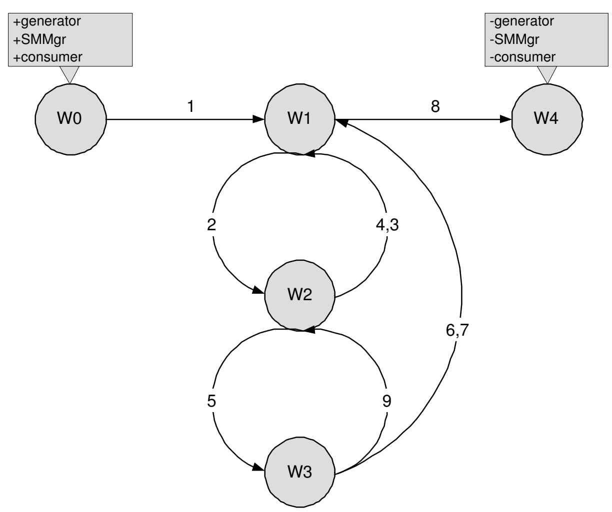

Figure 1.3. The secondary market scene.

4.2 Specifying the secondary_market scene

Three different roles participate in the secondary market scene:

SMMgr: The secondary market manager. Only one agent playing this role can enter into the scene.

producer: A power producer.

consumer: A power consumer.

The secondary market scene contains five states, the *W0* state is the initial, and it is in this state where all the participating agents enter into the scene. When all the agents are in the scene the *SMMgr* agent sends the *(1)* illocution to jump to the *W1* state where the negotiation between *consumers* and *producers* will be performed. When the *SMMgr* decides that the secondary market must be finished he sends the illocution *(8)* to inform that the market will be closed. After launching this illocution, the scene jumps to the *W4* state where all the agents leave the scene.

In *W1*, *W2* and *W3* states it is performed the negotiation between *consumers* and *producers*. When the scene arrives to the *W1*, each *producer* can start a negotiation process with a *consumer* sending an illocution *(2)* and jumping to the *W2* state. In this illocution the agent informs to the *consumer* about the quantity and price of the offer. At this state the *consumer* agent can do three actions:

1 withdraw the offer: illocution *(3)*.

2 accept the offer: illocution *(4)*.

3 generate a counter-offer: illocution *(5)*.

If the *consumer* generates a counter-offer, the scene jumps to the *W3* state, where the *producer* can accept the last offer, cancel the negotiation, or make a new offer: illocutions *6*, *7* and *9* respectively.

id	illocution	illocution constrains
1	(inform (?x SMMgr) (all all) start_secondary_market())	
2	(inform (?p producer) (?c consumer) offer(?quantity ?price))	(?quantity > 0 ?price > 0)
3	(inform (!c consumer) (!p producer) withdraw())	
4	(inform (!c consumer) (!p producer) accept(!quantity !price))	
5	(inform (!c consumer) (!p producer) offer(?quantity ?price))	(?quantity > 0 ?price > 0)
6	(inform (!p producer) (!c consumer) accept(!quantity !price))	
7	(inform (!p producer) (!c consumer) withdraw())	
8	(inform (!x SMMgr) (all all) end_secondary_market())	
9	(inform (!p producer) (!c consumer) offer(?quantity ?price))	(?quantity > 0 ?price > 0)

The rest of the scenes that compound the performative structure are specified in a similar way.

5. Step 3: The ABM

The third step in the methodology consists on the specification of the decision making for the agents that will populate the electronic institution specified in the previous step. As we have said there are three types of agents that participate in an electricity market: producers, consumers and the system operator. In the following sections we will describe each one of them.

5.1 Producers

Producers, as the name suggests, are responsible of generating the energy. In our example, energy can be generated using three different mechanisms: hydroelectric power stations, nuclear power stations and thermic power stations. Each type of power station is defined by four parameters:

- PowerUp. This parameter determines how much can be increased the production in this type of power station per time unit (in our case, one hour). This is a maximum and it is always conditioned to the total capacity of each concrete power station. For example, consider a power station that has a maximum production capacity of 800MW and the PowerUp for that kind of power stations is 200MW. If at time t that power station is producing 300MW it means that at time $t+1$ it can generate no more than 500MW.

- PowerDown. The same meaning that the PowerUp parameter but associated to the decrease of production.

- Cf. Cost per MW to maintain operative that kind of power station. To obtain the total cost for a concrete power station you have to multiply this value and the maximum production capacity. This cost is independent of the current production.

- CMW. How much it cost to generate a MW in that type of power station.

Each producer generates the energy using a different configuration of power stations. For example, you can have a producer that generates a 50% of the energy using nuclear power stations, a 30% using thermic power stations and a 20% using hydroelectric power stations. Taking into account this configuration and the parameters associated to each type of power station it is possible to calculate the capacity that has a given producer to increase or decrease the production per time unit (that is, the capacity to react to variations in the demand) and the cost of the produced energy.

To participate in the electricity market presented in section 1.4, a producer has to make decisions about three aspects:

- The amount of energy that will be generated during the next hour.
- The price and quantity of the energy offered in the double auction of the primary market.
- The negotiation process in the secondary market.

To decide the amount of energy to be generated during the next hour as well as the price to participate in the double auction of the next primary market, the producer uses a simple heuristic based on the result of its participation in the previous primary market. If in the previous round of the primary market the producer was able to sell the generated energy, then it will increase the production of each power station a quantity equal to PowerUp and will increase the price of the energy, otherwise it will decrease the production of each power station a quantity equal to PowerDown and will decrease the price of the energy. Concretely, producers use the following equations:

$$Q^t = \begin{cases} Q^{t-1} + PowerUp & lastSold = true \\ \\ Q^{t-1} - PowerDown & lastSold = false \end{cases}$$

where Q^t is the quantity produced at time t and $lastSold$ a flag that indicates if the producer was able to sell the produced energy the previous round of the primary market.

$$P^t = \begin{cases} P^{t-1} + \varepsilon^+ \cdot \frac{|P^{t-1} - AvP^{t-1}|}{AvP^{t-1}} & lastSold = true \\ \\ P^{t-1} - \varepsilon^- \cdot \frac{|P^{t-1} - AvP^{t-1}|}{AvP^{t-1}} & lastSold = false \end{cases}$$

$$FinalP^t = min(P^t, \text{Production\_cost})$$

where *Production_cost* is the cost to generate the energy (selling bellow that price implies the producer is losing money), $FinalP^t$ is the price that will be uttered in the primary market at time t and AvP^{t-1} is the price that was paid in the primary market at time $t-1$. $lastSold$ has the same meaning that in the previous formula and ε^+ and ε^- are two constants particular to each producer.

Besides the energy it has decided to generate, the producer is obliged to generate always an extra amount of energy equal to the 10% of its maximum capacity. This energy cannot be sold in the primary and secondary markets and has to be available to the system operator in order to balance the market if it was necessary as we will show in section 1.5.3.

A producer always offers in the primary market all the energy that it has decided to generate (Q^t).

In order to simplify the analysis of the results, the negotiation process of the secondary market has been reduced to a double auction between two participants. The price uttered by the producer is a constant that is particular to each producer and the quantity is always equal to the amount of energy that was not sold in the primary market. This constant together with ε^+, ε^- and the configuration of power stations are the set of parameters that define a producer's behaviour.

5.2 Consumers

The consumers that participate in an electricity market are companies that make a big consumption of energy, and energy wholesalers that later will sell the energy to smaller consumers.

Given the electronic institution presented in section 1.4, a consumer has to make decisions about three aspects:

- The demand of energy for the next hour.
- The offer to be uttered in the next double auction of the primary market.
- The negotiation process in the secondary market.

The demand of energy is modelled using real data. This data and the algorithm to generate the demand are the same that are used in the EBM model. Once determined the demand for the next hour, this demand is distributed equitably among all the consumers. Then, each consumer individually will try to cover that demand.

The strategy to participate in the double auction in the primary market is very similar to the one used by producers. The price is determined by the formula:

$$FinalP^t = \begin{cases} P^{t-1} - \varepsilon^+ \cdot \frac{|P^{t-1} - AvP^{t-1}|}{AvP^{t-1}} & lastBought = true \\ P^{t-1} + \varepsilon^- \cdot \frac{|P^{t-1} - AvP^{t-1}|}{AvP^{t-1}} & lastBought = false \end{cases}$$

where $FinalP^t$ is the price that will be uttered in the primary market at time t, AvP^{t-1} is the price that was paid in the primary market at time

$t-1$, *lastBought* is a flag that indicates if the consumer was able to buy in the previous round of the primary market and ε^+ and ε^- are two constants particular to each consumer. The quantity of energy requested is equal to the demand for the next hour.

As we have explained for producers, the negotiation process of the secondary market has been reduced to a double auction between a single producer and a single consumer. The price uttered by the consumer is again a constant that is particular to each consumer, and the quantity is always equal to the amount of energy that the consumer still requires to fulfill the demand after the primary market.

The price of the offer in the secondary market and the constants ε^+ and ε^- are the parameters that define a consumer's behaviour.

5.3 System operator

The task of the SO is to maintain the voltage level and dynamic security of the electricity network. Based on its analysis of the results in the primary and secondary markets, the SO can identify future shortfalls or excesses of energy and try to avoid them. After analyzing the situation after the primary and secondary markets there are several possibilities:

- The demand has been covered in the primary and secondary markets. The system operator notifies to the producers with energy that was not sold in the primary and secondary markets that they have to disconnect their power stations from the network. This measure is to avoid an overload that could be dangerous for the integrity of the network.

- There is some demand that was not covered after the primary and secondary markets. First, the system operator tries to cover the demand with the energy that will be generated but that was not sold in the primary and secondary markets. If after that there is still demand to be covered, the system operator uses the 10% of extra energy that each producer is obliged to generate specially for these occasions.

The price that will be paid for the energy assigned by the system operator is the average cost of all the energy that is going to be generated by producers (including the energy that has not been sold).

6. Step 4: Multi-Agent System

The final step is to build the multi-agent system that implements the electronic institution presented in section 1.4 and it is populated by instances of the agents presented in section 1.5.

In our experiments we do not have real agents running in parallel and exchanging messages through a communication platform. Instead, agents are implemented as C++ classes and the exchange of messages is done through method calling. This allows us to run the experiments very fast without compromising the validity of the obtained results.

7. Cycle P4 through evolutionary computing

To explore the different configurations of agent instances to build the multi-agent system and to find which of those configurations satisfy the requirements fixed by the EBM in the first step of the methodology, we propose the use of evolutionary computing. In the following sections we will explain in detail how this approach is applied in the electricity market scenario.

7.1 Gens and chromosomes

A multi-agent system is fully specified by a chromosome. Each gene of that chromosome contains the information that defines an agent. In the electricity market scenario there are two types of agents that we want to explore: producers and consumers.

As we have said there are five parameters that specify a producer:

- The configuration of power stations that determines how the producer generates the energy. There are three parameters, each one representing the different types of power stations: Hydroelectric noted as PS^H, Nuclear noted as PS^N and Thermic noted as PS^T.
- ε^+ and ε^- that define the strategy of the producer to fix the prices in the double auction (primary market).
- The negotiation price, noted as NP, that defines the price the producer will offer in the secondary market.

and three parameters that specify a consumer:

- ε^+ and ε^- that define the strategy of the consumer to fix the prices in the double auction (primary market).
- The negotiation price, noted as NP, that defines the price the consumer will offer in the secondary market.

To simplify the genetic operations (mutation, crossover, etc.) we have unified the length of the genes in the chromosome. Parameters PS^H, PS^N and PS^T are used also to represent a consumer but only for syntactical reasons and they are always are equal to 0. Figure 1.4 shows a chromosome codifying a multi-agent system for the electricity market.

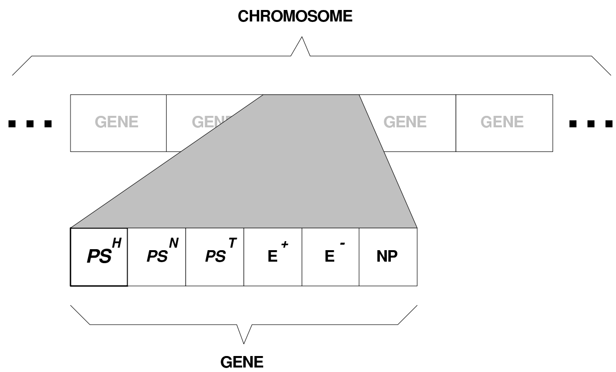

Figure 1.4. A chromosome for the electricity market

It is important that the gens of the chromosome fulfill the following restriction: $\sum_{i \in n} PS_i^H = 1$, $\sum_{i \in n} PS_i^N = 1$ and $\sum_{i \in n} PS_i^T = 1$ where n is the number of genes. To achieve that, we have to normalize these parameters in the chromosome after applying every genetic operator.

7.2 Fitness functions

We use the aggregation of three different functions to evaluate the fitness of an individual (MAS):

1

$$f1 = ac\left(\frac{100 \cdot |AvABM - AvEBM|}{AvEBM}\right)$$

This function computes how near is the average cost of the electricity produced in the MAS ($AvABM$) with the average cost of the electricity we have calculated using the EBM ($AvEBM$). The ac function is defined as:

$$ac(x) = \begin{cases} 1 & \text{IF } x < 8 \\ 1 + \frac{(8-x)}{7} & \text{IF } 8 \leq x \geq 15 \\ 0 & \text{OTHERWISE} \end{cases}$$

2

$$f2 = ed\left(\frac{100 \cdot PowerDeficit}{Production}\right)$$

This function computes the percentage of power deficit relative to the total production. The ed function is defined as:

$$ed(x) = \begin{cases} 1 & \text{IF } x < 1 \\ \frac{(3-x)}{2} & \text{IF } 1 \leq x \geq 3 \\ 0 & \text{OTHERWISE} \end{cases}$$

3
$$f3 = pl\left(\frac{100 \cdot PowerLost}{Production}\right)$$

This function evaluates the power lost in our model (power that is produced but is not consumed). The *pl* function is defined as:

$$pl(x) = \begin{cases} 1 & \text{IF } x < 8 \\ \frac{(10-x)}{2} & \text{IF } 8 \leq x \geq 10 \\ 0 & \text{OTHERWISE} \end{cases}$$

The formula to compute the fitness function is:

$$Fitness = 0.4 \cdot f1 + 0.3 \cdot f2 + 0.3 \cdot f3$$

7.3 Description of the experiments

The aim of the experiments is to find a MAS that converges with the EBM in three aspects:

- The average price of the electricity in the market during the analyzed period. We have analyzed the market using the EBM during 720 iterations (equivalent to one month) and the average price obtained was 39.16. This is the value that we want to achieve using the ABM.
- The percentage of demand, relative to produced energy, that cannot be fulfilled. Here we will not tolerate a percentage greater than 5%.
- The percentage of power relative to the total production that is lost (power that is generated but it is not consumed) . In the EBM we found that the amount of power produced that is not consumed was about an 8%.

The general parameters of this experiments are the following:

```
PARAMETERS FOR THE GENETIC ALGORITHM:

numInd       =  50     // Number of individuals in each population
xoverpr      =  0.1    // Crossover probability
mutpr        =  0.05   // Mutation probability
fitnessThr   =  0.9    // Threshold for the termination condition
minimumFit   =  0.7    // Mininum acceptable fitness for the
                       // termination condition
EBMAvCost    =  39.16  // Average price of the electricity in the EBM
ProdDeficit  =  5      // % of demand not fulfilled
                       // (relative to the total production)
LostPower    =  8      // % of power that is produced but it is not
```

```
                         // consumed (relative to the total production)
```

The termination condition imposed to the genetic algorithm is that the best individual of the population have to fulfill the following conditions:

- The average fitness after 15 executions of this individual must be greater than *fitnessThr*.
- The minimum fitness after this 15 executions must be greater than *minimumFit*.

This restrictions guarantee that the individuals are good and robust enough.

```
PARAMETERS FOR THE MAS:

numRounds  =  720  // number of electricity market sessions

   PRODUCERS:
   numProd                 =  30    // number of producers
   EupProd                 =  [0.05,0.15]
   EdownProd               =  [0.05,0.15]
   NegoProd                =  [25,60]

   CONSUMERS:
   numCon                  =  60    // number of consumers
   EupCon                  =  [0.05,0.15]
   EdownCon                =  [0.05,0.15]
   NegoCon                 =  [10,45]
```

EupProd and *EdownProd* are the possible range for parameters ε^+ and ε^- respectively in the case of producers and *EupCon* and and *EdownCon* are the possible range for parameters ε^+ and ε^- respectively in the case of consumers (see section 1.5.1 and section 1.5.2).

NegoProd is the possible range for the negotiation price in the secondary market for producers and *NegoCon* is the possible range for the negotiation price in the secondary market for consumers.

Each electricity market session implies the execution of the primary market, the secondary market and the balancing market plus the settlement of the exchanged tickets (generation and payment of the energy). Because this happens every hour, by running 720 sessions we are simulating one month (720 / 24 = 30).

The fitness function used in these experiments is the one presented in section 1.7.2, that is:

$$Fitness = 0.4 \cdot f1 + 0.3 \cdot f2 + 0.3 \cdot f3$$

where $f1$ computes how near is the average cost of the electricity produced in the MAS, $f2$ computes the percentage of power deficit relative to the total production and $f3$ evaluates the power that is produced but is not consumed.

7.4 Results

In all the experiments, after about 20 generations the genetic algorithm was able to find an individual that fulfilled the requirements established by the EBM and described in previous sections.

8. Conclusions

EBM and ABM are two well known styles of computer based modeling. EBM has a long tradition and a selection of friendly tools, ABM is a more recent but a powerful approach. EBM allows the modeling of the global behaviour of a population leaving implicit the behaviour and interaction of individuals. On the other hand in ABM we model explicitly these individuals and their interactions leaving the global behavior of the population as an emergent result. There are numerous applications of each of these approaches [6, 5]. They have even been applied to the same problem in order to establish comparative criteria about their alternative use [3]. This competing view between EBM and ABM makes sense if you have a real system against which the model you build should be checked. However if the goal is to build an artificial system whose behavior is to be inspired by a real system but not bound to simulate it faithfully, then the reasonable attitude is to take EBM and ABM as complementary approaches to be used at different levels of abstraction in the design lifecycle.

We have integrated both approaches into a methodology for MAS design and implementation. More specifically we have used EBM to identify desired global properties of the MAS. Then we analyzed how the flows of the EBM could be produced by the interactions between different types of agent. The structure of the EBM guides the definition of these interactions through an electronic institution. We then decide on the agent model we expect that will allow populations whose aggregate behavior will meet the EBM. Finally, the model parameters become the genes of agents in the MAS when exploring the space of models using evolutionary computing.

The application of evolutionary programming techniques to MAS redesign brings us several preliminary results.

- The chosen agent model allows the convergence of the evolutionary process towards the production of a stable collection of MASs showing the EBM specified properties to an acceptable degree. This is so in a huge search space. This shows that the choice of GAs as a basic technique for SADDE is justified.

- We found that once a good ABM model is engineered to match the behaviour predicted by the EBM, it is not easy to populate a MAS by fixing the agent parameters. Initial populations with randomly fixed parameters show a very bad global behaviour. This can be due to the fact the the ABM model does not impose enough constraints on the behaviour of agents and therefore the space contains big areas where the behaviour is not good enough.
- According to several robustness experiment we see that once a stable population is found up to a 20% random changes in the individuals can be tolerated within acceptable ranges in the fitness function.
- The fact that a GA converges starting from an initial MAS at Step 4 of the SADDE methodology proves that the model chosen for the ABM at step 3 in SADDE is feasible to show the behaviour specified at the EBM. A failure on this would mean that the ABM model is not appropriate.
- Finally, we have observed through experimentation that societies with a high interaction degree show more stable behaviours.

We intend to continue the research in the area of complex systems as we are convinced that if a robust methodology has to be found to develop MAS it has to deal with the highly non-linear problems that systems composed of thousands of autonomous entities raise. Agents have lost the composability that was natural in all computing paradigms from functional to imperative to object oriented. Autonomy has open the door to many unanswered questions that currently prevent from having robust methodologies.

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