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SMART GRID: FROM RAW DATA TO A DIGITAL MODEL

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ABSTRACT

One of humanity's main objectives in the years to come is to drastically reduce our greenhouse gas emissions and to ensure energy efficiency. But at the same time the need for electrical power is rising and new products, requesting great amounts of electrical energy, such as electric cars and IoT(Internet of Things), are introduced in the market.

Reaching governmental and world goals about energy transition can only be made through the massive integration of renewable energy sources into the electrical grid. The sources of renewable energy being decentralized, it is necessary to design an adapted energy grid to handle them. To face this challenge, simulation tools and numerical methods must be used to optimize transport, distribution and consumption of electricity, hence there is a need of prediction and forecasting tools.

Different physical factors are involved in the electric power transmission, such as impedance, intensity, conductor's properties and weather. Using these different factors, we can build different algorithms calculating voltage in real time in every cable. These estimations will enable electricity to take the optimal path to decrease lost.

Renewable energy production being irregular, increasing their number implies to predict consumptions and energy storage or discharge in real time. This is why the consumption patterns of every device connected to the grid must be organized in order to optimize the global consumption of the grid with the use of a combination of several fields such as game theory, IoT and grid's communication and artificial intelligence.

Keywords: **Multi-Agent Systems, Agent-Based Model, Complex System, Game Theory**

1. INTRODUCTION

We are facing many challenges today regarding energy. It has become clear that it is essential to diminish our greenhouse gases to decrease the impact of the human's activity on the environment. Furthermore, our current energy consumption is made in such a way that a great deal of our energy is being lost during transportation, or is lost because we are unable of evening and balancing demand and consumption, making overproduction the only way to avoid power outage. Finally, the important daily consumption peaks require the use of fossil fuel power plants: polluting but reactive enough to adapt to such quick increase of consumption.

Since COP21, France has made the engagement to diminish its greenhouse emission by 75% by 2050 compared to 1990. But the consumer's comfort must suffer as little as possible from the changes made to the energy system. So we must give the same services for a lower energy consumption, we must therefore increase energy efficiency in the French electrical network.

Furthermore, such development could be made in an increasingly decentralized way and come from the initiative of citizen or collectivites. The European Economic and Social Committee (EESC) concluded, in a report of January 2015, after the study of European example, that the deployment of renewable energies was more present and faster in the states which gave the citizen the possibility to start their own energy initiatives. It advocates to the states to have as a priority to allow the citizen to make the subject of renewable energy production their own.

To face those challenges, it is necessary to rethink the electrical network. It will have to integrate the recent technological breakthrough from a variety of different domains to allow a smarter and a more environment friendly production. This new grid has a name: The Smart-Grid.

A Smart Grid is an intelligent energy grid [5] : it means that it is capable of adapting, predicting and communicating with the different agents it is interacting with (production, consumers, weather...) to optimize production, transport and consumption of energy. It can be seen as a complex system optimizing efficiency, reliability and robustness of the electrical grid. It is made of intelligent nodes interacting autonomously to deliver power to the consumers by integrating advanced control and communication techniques.

It can be divided in three parts:

- The devices: consuming, storing or producing energy.
- The micro-grid: those are the nodes of the grid. They have the size of Eco-district; they manage distribution of energy to (and between) the devices.
- Transmission[6]: the energy circulates in the high-voltage cable from the power plant to the transformers where it is distributed in low or middle voltage in the microgrid.

2. TRANSMISSION

The demand of electricity has already increased of 25% since 1990. The transmission of the electricity consists of routing energy produced by different centers of productions to consumers.[8]

A high voltage(400 or 225 kV) [7] must be maintained to avoid significant losses during transport, mainly due to the Joule effect.

Presently, the network market doesn’t work in real time but from predetermined situation. The network is composed of intensity and voltage sensors on the lines taking measures on the networks, mainly at the transformers and the electricals stations. The aim of our project is to adapt the lines in real time, dynamic line rating [3] and integrating others factors like weather to choose the best way for the electricity. The weather is a new factor important with the objectives of the important integration of renewable energy. The self-healing of the network is also a new objective.

Our aim is to use physical data of the network and to transform them in numerical data, in a graph. It’s important to use numerical data[1], because the numerical calculations are more reliable and faster than human calculations. Moreover, the data must be collected directly at the root. We want to avoid the losses that are too important and optimize the routing of process.

2.1. From physical data to numerical data

In this part, we focus on a small part of the French network. We realize the routing between the city of Beaulieu and Niort. The lines between the two cities have a voltage of 225 or 90 kV. The aim is to have the maximum flow at the lowest cost.

In the first step, we realize a curve of power as function of cost. We have obtained the following formula with the ohm’s law.

$$Losses = RP^2 / U \quad (1)$$

U refers to voltage in Volt
P refers to power in Watt
R refers to resistor in ohm
Losses refers to losses in Joule

With this formula, we have the voltage of the lines from maps of RTE (French Electricity transmission network). We have as unknown the power and the losses.
To find the values of the resistors we use the Pouillet's law because we know the section and the materials of the lines(see Table1). We see that the losses are more important when the power is higher.

Table 1. Table of resistor values

Lines	Voltage(kV)	Value of resistance(ohm)
1-(54km)	225	0,918
2-(30km)	225	0,51
3-(35km)	225	0,595
4-5-(13km)	225	0,221
6-7-8-(3km)	90	0,1275

In the second step, we realize three linear regressions on the curve that we obtained before, where the using rate is the most important on the lines, because we know that the lines are more used for a certain power. For example, the lines with a 225 kV voltage, the using rate is more important between 200 and 340 MW. When we realize our linear regression, we obtain the equation ax+b. The coefficient **a** represent the cost of the losses in Joules. The coefficient **a** changes in function of the power in the lines. With these coefficients, we can modelize our lines from the cost and the capacity(power of the lines).

2.2. Numerical data

We want to take the physical data, and transform it in graph to apply the Busacker & Gowen algorithm. The complex network theory is important for the complex system such as Smart Grid, and provides mathematical tools to model its structure.
The complex network of Smart Grid change at each time, so it's important to model this functions by taking into account the dynamics[2]. The separation of each criteria in a dedicated graph (like voltage or…) is important to simplify modelling. The overall adhesion function is defined as an aggregation of several spaces.
In this manner, a modification in a space is instantaneous. The Smart grid is governed by a number of qualitative and quantitative criteria, for example the voltage of the power lines or the weather, etc. Finally, graphs are a very useful modelling tool in the context of complex systems to manage acquaintances between agents and be able to follow the dynamics of relationships between them. [10]

Now that we have modelized our lines numerically, we want to choose the best path between all the lines (meaning the path with maximum flow and the minimum cost) [4].

We represent our lines this way:

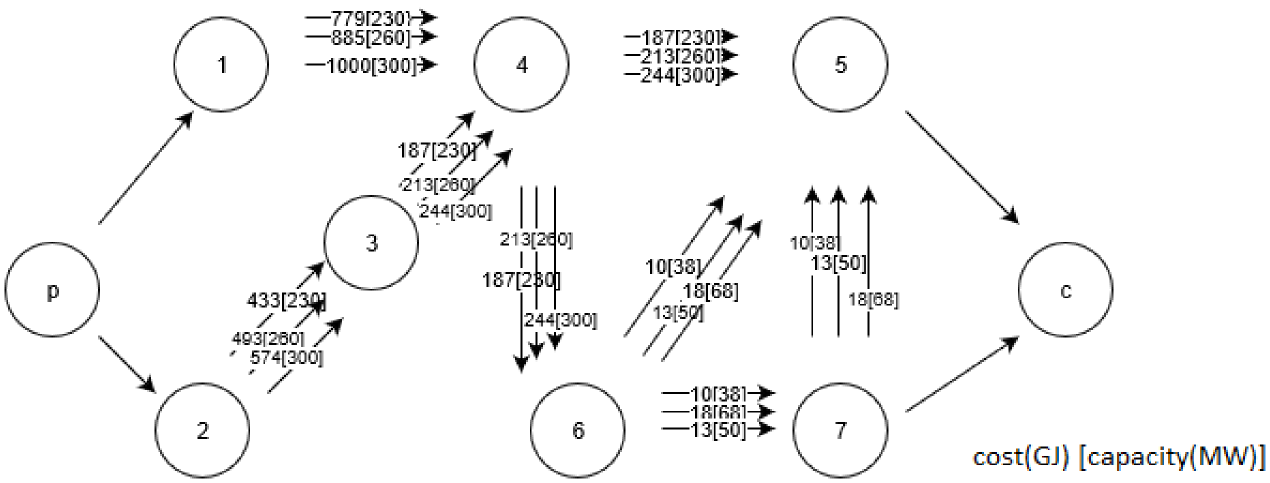

Fig. 1. Graph representing the electric lines in function of cost and capacity

To choose the best path, we search the minimal cost. At each iteration we want to determine the shortest path using only the cost. To find the shortest path we use the Bellman Ford Algorithm (Fig.1). Next, we saturate the founded path, we watch the capacity minimum on the path, and we send the new flow cost:

$$New\_flow\_\mathrm{cos}t = \left(\sum_{i=1}^{total\_line} \mathrm{cost}\_line_i * x_i\right) * (\min(non - zerovalues\ from\ \ capacity\_line_i * x_i)) \quad (2)$$

x_i : x_i =1 if the line i is used otherwise x_i =0

We compute the shortest path, and if it is the end of the algorithm, there is no path between producers and consumers. The total cost is equal to:

$$\sum_{i=1}^{total\_line} flow_i * \mathrm{cost}\_line_i \quad (3)$$

total_line: Total_line is the entire number of lines of the network (Figure 1)

2.3. Analysis of data

We want to understand where the flow is saturated if the demand is growing. We don't consider the cost now. We have two schemes, the augmenting path and the flow max at the min cost. The min-cut give information where the grid has bottleneck. A min-cut at a source means the production isn't enough. A min cut at a sink means the consumption is well defined. A feed back to the consumers actives a process that determines a new path for electric transmission. Then, routing is updated, ect. Until demand is equal to consumption.

When a consensus is reached, we don't use the data at the consumption level[11]. We use a weighted average formula to estimate the consumption of each microgrid.

$$2\sum_{x=1}^{n}\frac{f_{i,x}x}{n(n-1)} \quad (4)$$

Where **f**i,x is the flow which arrive or depart of **i** at the **x** occurrence.

Now, we want to realize the feedback if the demand isn't satisfied. The feedback are composed of two steps, first we put the producers to infinity and we realize the min cost flow. If the demand isn't satisfied we have two solutions, decrease the demand or look the cut min to see if it's a lines problem. The second step consists of putting the consumers to infinity and realizing the min cost flow. If the consumption is too high, we need to increase the production, and if there is a problem on the lines we must decrease the demand.

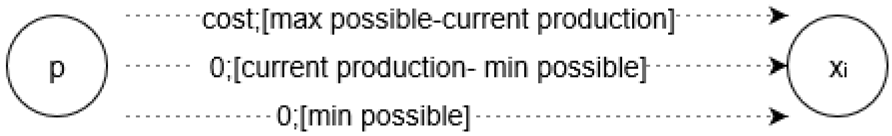

Fig. 2. Minimum and maximum variation production of power stations

Max possible: Max possible is the maximum evolution of the production in comparison with iteration i-1

Min possible: Min possible is the minimum evolution of the production in comparison with iteration i-1

x_i : x_i refers to the consumers

P: p refers to the source of production

We can see the current production in the middle edge(Fig.2). In the upper edge we see the maximum production and the cost of this evolution. In the lower edge we can see the minimum production.(Fig.2)

The last step consists of scheduling the production. Each plant has a known variation across time. In order to find the best schedule of production for the next step (i.e in 5 minutes), we use both known variations and the estimated consumption from formula (3). Thus, each source of the graph has three acts of increasing cost where the first one refers to the lowest value, the second to the current production and the last to the highest value. Cost of each areas depends of the kind of the plant (coal, nuclear, etc.).

3. DISTRIBUTION: THE MICRO-GRID

The main challenge in distribution and consumption of energy is avoiding the formation of daily consumption pikes and levelling consumption of the grid in general. Today no satisfying solution have been found to answer those challenges, and creating a model of efficient management of consumption is a key step in the creation of a microgrid.

Demand-Side Management (DSM) is the management of demand in order to reduce and to level consumption. Automating this decision making to optimize consumption is called Demand-Response (DR). It is on the DR aspect of DSM (automatization of demand-side management) that we are going to focus on in this part of the article.

Such a heterogeneous and large system as the micro-grid needs physical data-processing, and mathematical tools to be apprehended. In this context, complex systems theory is important to approach the concepts of microgrid and Demand Response as explained further in the article.

3.1. Decentralized demand-side Management

It would be tempting to centralize decision making, to organize consumption from a “higher point of view”. But centralized control of thousands of smart meters would be an extremely complex task. It would require an enormous calculation power and would be problematic regarding private life of the users. Indeed, it needs an exhaustive knowledge of the device, the habits and preferences of each users.

Hence the notion of Decentralized Demand-Side Management (DDSM), in which the system is self-organized and therefor does require a central intelligence, but creating an efficient DDSM is a complex task.

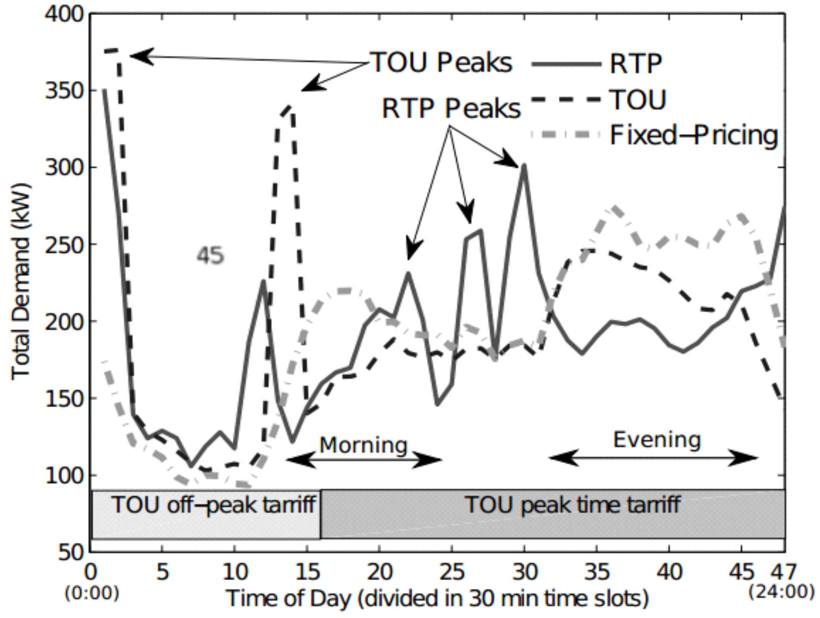

Fig. 3. Consumption curves of a modelled micro-grid with different price incentives. [12]

Indeed, on this graphic representing the different consumption curves in function of the different DR types we can see that the use of real time pricing (RTP) as the use of Time of use (TOU) - created to optimize consumption - are actually creating induced peaks. It is therefore very important to develop new tools allowing us to organize the consumption without those important drawbacks [9].

3.2. Definition and application of game theory and complex system

The consummers in a smart grid can be seen as several agents acting according their own rules and with the objective of maximizing their gains (in this case it would be compfort: consuming as much as you want when you want for as little as you want). Developing the rules that define the consummers and the smart grid so that by acting in their interest the “players” (consummers) also act for the common good (the whole grid) is apllying game theory to electricy consumption. A system composed of a large population of connected agents is said to be complex if there is an emergent dynamic resulting from the actions of every of the agents rather than imposed by a central intelligence. Their collective self-organized behaviour is hard to predict by locally observing the behaviour of the agents [13, 14]. The microgrid matches perfectly this definition and therefor represents a complex system. To study it and create an efficient model it is therefore necessary to use the tools allowing us to study complex systems. We created our model by using a multi-agent modelling environment (NetLogo).

3.3. The model

Our model represents a small microgrid composed of four buildings. Our goal is to obtain a minimal consumption for a maximal comfort and to avoid brutal changes in the global consumption of the microgrid. This will be achieved by having each device to adapt accordingly to the global situation of the microgrid. Our goal is to even consumption, to diminish the amplitude of the peaks

In each of the houses there are a number of devices, each of a different breed: some have batteries others don't, some are cyclic other aren't etc. These devices are going to turn themselves on or off according to their own set of functions and rules. Their behaviour will depend on global variables of the microgrid (global consumption of the microgrid, time of day…) as well as on local variables (consumption of the house, current agent state, value of its batteries, and the steps of its consumption patterns…).

Each agent represents a device with its parameters and values. The device will choose a consumption scheme according to his situation. The devices with a battery can choose to charge or to discharge their batteries. The devices may choose to defer their consumption if they can. This way each device, in function of its different properties, has a variety of schemes it can choose to adopt.

With regulation activated in the microgrid, each device will be able to attempt to regulate the system according to this principle: if the global consumption goes beyond the average value plus a tolerance value that is specific to the device, then the devices will set itself on battery mode so that the global value gets closer to its average value to avoid important variations. If every device had the same threshold tolerance value, then they would all react at the same time, causing an important variation in the global consumption (see figure 3) and therefor a peack. Therefore, the variation of the threshold value has to be adapted to the system so that it stays stable. The same principle is applied for the deferable devices.

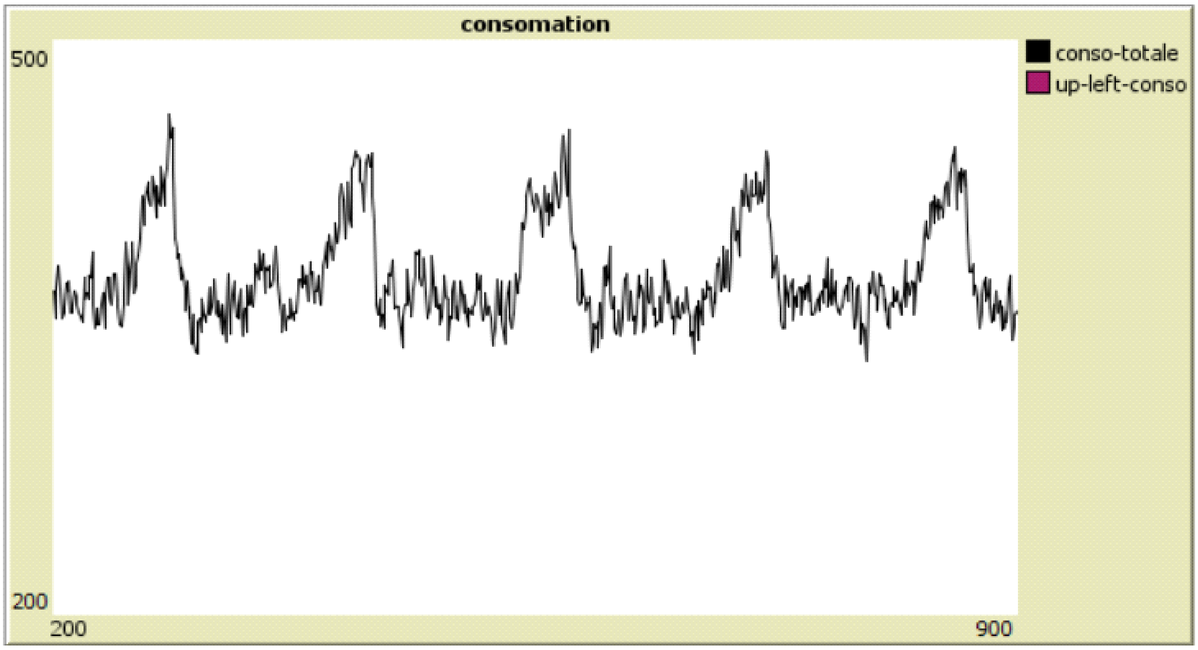

Fig. 4. Consumption curve of the model in function of time

The global consumption is a cyclic curve. In the "evening" the consumption grows higher and falls rapidly after midnight. The model has been studied running with three different kind of operation, the first without any regulation, the second with a well-adjusted regulation and the third with an improperly adjusted regulation. The unit of time is of 1/144 of a day.

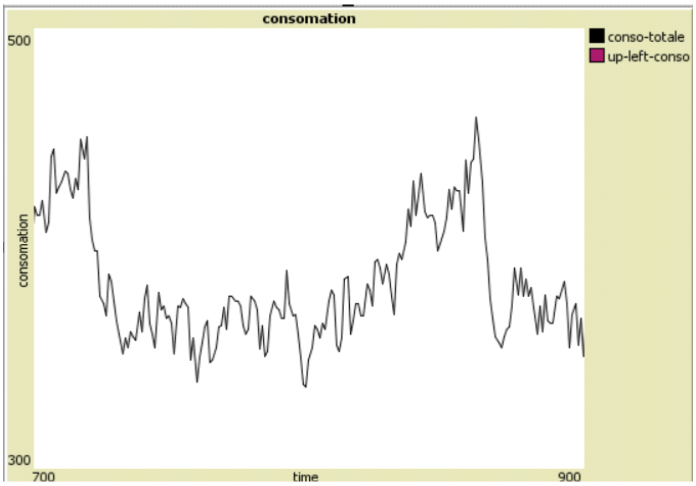

Fig. 5. Curve with no regulation

We can see in figure 5 the curve representing the consumption in function of the time during a "day" with no regulation.

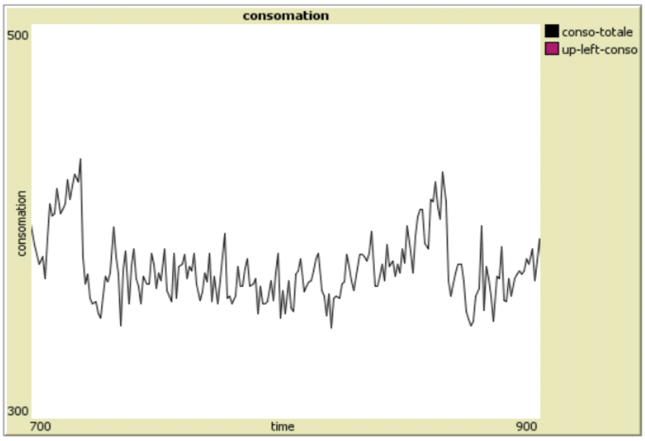

Fig. 6. Curve with a well-adapted regulation

With a well-adjusted regulation, it is visible on figure 6 that even though the consumption is far from being smooth (due to the small number of devices) we can see that the pikes are much smaller than with the non-adapted regulation, and that in general the values stay always closer to the average.

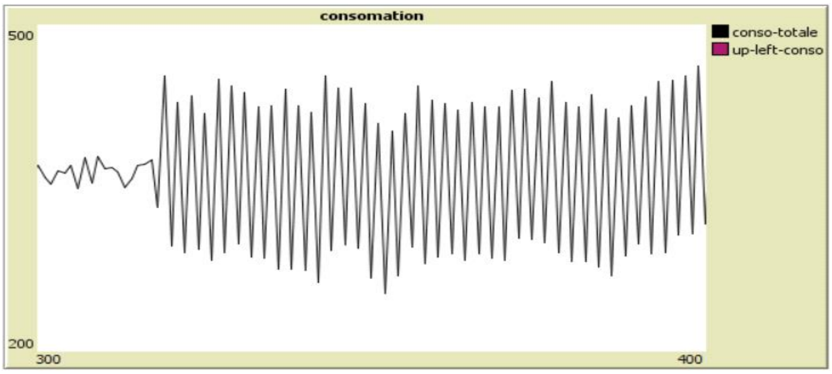

Fig. 7. Curve with an ill-adapted regulation

The devices can have a response that is not adapted to the grid. For example if they are too reactive (as a whole) they will put the system off balance. In the case of a regulation that is not well adapted to the size of the grid (Fig. 7) the answer of the devices facing an under-consumption or an over-consumption will be too important and the system will become unstable. It can be explained by a bad repartition of the "consumption-mode-changing-threshold-value" (the consumption value of the grid that makes the device change his mode of consumption). The solution to this issue was to create a process in which the consumption-mode-changing-threshold-value of the device is updated regularly so it can adapt to the changes in the grid (Fig. 8).

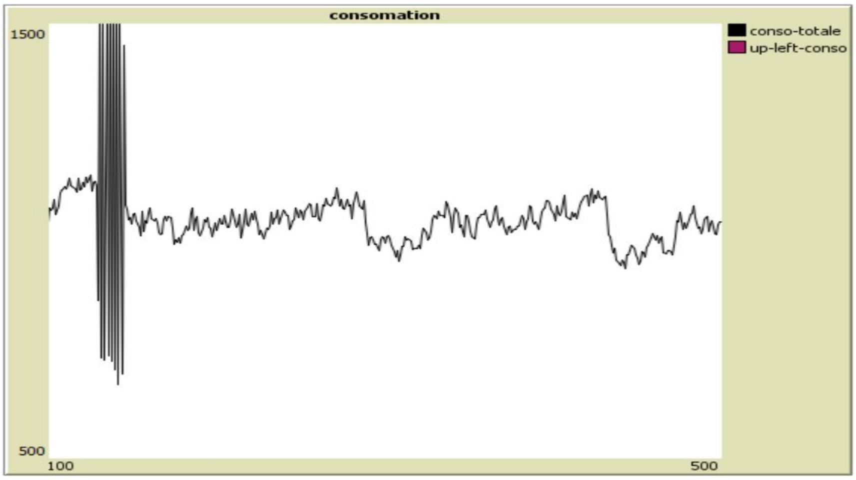

Fig. 8. Curve with auto-adapting regulation

Here, the regulation was started around 140 ticks (unit of time). The system went off balanced, but by adjusting its threshold value, it managed to find balance again.

4. CONCLUSION

A Smart Grid is a complex and constantly evolving system. This is why we must use adapted tools of simulation and prediction.

For the routing of electricity, we recover physical data, and we include this data in numerical graph. From this graph, we can establish the best path to deliver the best flow at minimal cost. The energy distribution agent-based model was based on Decentralized-demand-side-management. Composed of intelligent devices adapting their consumption schemes to the state of the microgrid, it was able to significantly even consumption and diminish major pikes. It is a case study of decentralized-demand side management using intelligent devices with positive results.

Thus, whether it is transmission or distribution, modelling seems to be an essential element in the creation of a functional Smart Grid.

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