Modeling Strategic Bidding in Congested Electricity Lines

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Preface

This document represents the final report of the Master Thesis Project which concludes my MSc. education in "Engineering and Policy Analysis" (EPA) at Delft University of Technology. The work was performed at the section: Energy and Industry.

One year back when I took a class at TU Delft, I was amazed how electricity could be traded as any other commodity in the market. The whole liberalization process attracted me since I thought that one company should be in charge of generation, transmission and distribution of electricity since it could create a lot of problems if not. I was not totally wrong, although the once vertically integrated electricity undertaking can be unbundled in different pieces; it could creates a coordination problem.

I was interested as well in modelling paradigms which, more than provide forecast which never take place, give insight of the world itself. The combination of these two areas was a challenge but gave me invaluable of both. This research project would not have been possible without the support of many people. Their direct and indirect contribution permitted me to undertake my studies.

First and foremost, I would like to express my appreciation to the members of my committee. Their support, guidance and encouragement enabled me to develop an understanding of the subject. Gerard, your critical comments about the importance of a sound report made me realize the importance of being consequent and clear. Laurens, lots of thanks for your ideas, comments and an endless stream of articles; your supervision and insight encouraged me. Igor, your sincerity and patience helped me to improve my modelling skills. Scott, I appreciated the interesting discussions we had, and your remarks to improve the quality of the thesis.
I would like to especially thank Mamadou D. Seck, who although is not part of my thesis committee, he patiently gave some ideas and explanations of Java which I was not familiar with.

Second, lots of thanks are due to all my friends with whom I shared these last two years. Thanks to you, I had a brilliant time balancing studies and fun. Jing, Nan, and Lin, I will never forget our international dinner and great chats about everything and nothing. Tewes Zeef, I would like to thank for your out-of-the-box ideas and great moments of fun with the RCC. Luis, you are an incredible friend as your are a brilliant cook and you are guilty for some kg that I gained. Sergio, Carlos, Bernardo, and Amilcar; your enthusiasm and encouragement helped me in good and bad times giving me new lights. Giuseppe I appreciate your comments and your advices. Salvador, thank you for your advice, support and the laughs which eased the time I spend studying.
Alonzo, I deeply thank you for your patience, friendship and invaluable guidelines which have inspired me to move forward.

Finally and most importantly, I would like to thank my family for their constant support and love. In particular to my mother, father and sister who gave me cofidence; and my grandfather who always believed on me. For all of you, this is for you..

Enrique Backhaus
Delft, August 2010

Summary

The ongoing liberalization process has increased the complexity in coordination amongst the parties which once formed part of one single vertically integrated undertaking. Basically, Producers or suppliers, submit their willingness to produce electricity in terms of bids which are matched with the demand curve of Consumers. In some market arrangements, the lines' capacity is not taken into account and the resulting electrical flows could be beyond the lines' capacity. This situation is known as congestion, and could create opportunity for Producers to manipulate the market outcomes like in California and England. Policy makers need proper decision tools design which give insight of the electricity markets in case of congestion. Based on these arguments, this thesis raised the main research question:

How could market power, in the case of congested electricity lines be modelled?

The research suggested that the electricity markets are Complex Adaptive Systems because the market participants cooperate and coordinate the trade and transmission of electricity. The system was analyzed by means of Agent-Based simulation which gave the states and rules of the market participant. One important rule that governs the Producers' bid process was represented by the algorithm Prove and Adjust developed by Kimbrough and Murphy (2009). Basically the algorithm represents a trial-and-error process that Producers undertake with fictitious bids before taking a decision on their next bid. The simulation gave important and insightful results regarding the algorithm applied both cases, no congestion and congested lines.

The simulation achieved the optimal profit maximization point in case of monopoly, and Cournot price for the Producer with the highest bid in duopoly. From the former case, the model's results indicated that a trade-off needs to be done when choosing the learning time that an agent needs to take a bidding decision (go up or down of its current bid) so as converge into the optimum. If the learning time was large, then the convergence was almost sure with small deviation but it took a lot of computational time. On the other hand, if the learning time was small, the price-bid path had a lot of deviation, but low computational time. As well, if the increase on the price-bid position was too large there was no convergence, but if the value was too small then it required a lot of computational time. In congested lines managed by re-dispatching, the agents out of the merit order but which are needed to supply electricity within security limits increased their price-bid up to a cap. These Producers bid prices different from their marginal cost, and thus they exerted market power following their profit maximization nature.

Keywords: agent-based simulation, electricity market, congestion management, market power.

Contents

List of Figures

List of Tables

Clarifying Definitions and Concepts

Across the consulted bibliografy, different terminologies are used to refer to the same term which could produce confusion. Therefore, for the purpose of this master thesis, and to avoid discrepancy the definition and concepts used thereof are extracted from the main literature or the most common terminology used across the scientific publications. The terminology used has been clustered into *wholesale electricity market* terms and *agent-based simulation model* terms since both represent the principal area used in this thesis.

Wholesale Electricity Market

The most common terminology used are in concordance with the *European Commission* terms[1] or with the principal literature in electricity markets.

Regulation Legal instrument used by the European Commission that extablish binding legal force throughout every Member State, on a par with national laws.

Directive Legal instrument used by the European Commission that sets out broad principles, leaving Member States the means of achieving the priciples' objectives. Directives differ from regulation in the sense that directives are addressed to national authorities, who must then take action to make them part of national law, and decisions, which apply in specific cases only, involving particular authorities or individuals.

Transmission System Operator (TSO) Body in charge of energy balance (system operation) and transmission line operation. The EC uses the terminology Transmission System Operator (TSO) and Independent System Operator (ISO), both have the same role but they differ in the ownerghip of the network. While TSO is fully unbundled from competitive activities being the owner of the network, the ISO takes care of operational aspect of the network without owning the network. For the scope of this thesis, it will be used the term TSO.

Producers Actors in charge to generate electricity. Their willingness is represented by a bid offered to the TSO.

Customer Actors who demand and consume electricity. This includes domestic, commercial and industrial consumer.

[1] Regarding the Directive: 2009/72/EC (which repeals Directive 2003/54/EC with effect from 3 March 2011) ; and Regulations: (EC) No 713/2009 and (EC) No 714/2009

Interconnectors Physical links between national electricity grids. This links are called cables, and serve as media to support the flow of electric charge.

Capacity Maximun ability of a producer to generate electricity in a given time. Measured in unit of power, kW or MW. The actual energy produced depends on the load factor.

Load factor Ratio of actual energy output over a period of time and its energy output if it had operated at full capacity over a period of time.

Marginal cost Cost of the next kilowatthour generated. The profit maximization output is achieved when marginal cost equals marginal revenue.

Revenue Income that an undertaking receives for the its activity. In case of producers, the revenue is equal to the product of electricity output time the price of the market.

Settlement period The time period for which the bid is made. Usually schedualed in hour or half-hour periods.

Bid Production offer in terms of quantity of electricity and the price at which they are willing to produce it.

Market clearing price When the .. is closed, the market operator or the system operator, in case of decentralized and centralized markets respectively, match the supply and demand. In the case of uniform auction, only the suppliers bid into the market.

Price-setting producer The most expensive producer in the merit order.

Pool market Centralized market arrangement in which no physical, bilateral transactions are allowed besides the mandatory pool.

Marginal unit Producer unit which establish the price of the clearing process.

Clearing process Procedure in which the market operator matches the supply from producers and the demand from consumers. The result is the pair price and quantity of electricity for everty settlement period.

Merit order Order that a system operator will place producers based on their cost to supply certain quantity of electricity. Those producers which are in the merit order, are despatched.

Bus Point where produced electricity enters into the network or leaves to be consumed.

Spot market Market in which electricity is traded for the next day for every settlement period. There result will be total quantity to be produced at a given price. There will be only one electricity price in case of the market operator uses the uniform auction and different prices (at each node) if marginal cost is used instead.

Agent-Based Simulation Model

The particular modelling definition and concepts in its majority in corcondace with the definitions from the work presented by Igor, 2008 and relevant literature in agent-based modeling.

Complex A system which cannot be fully described by a single formalism.

System A set of interacting part which form a unified whole.

Formalism Set of independent concepts and perspectives which describe characteristics of a system. Formalisms are independent between each other in the sense that no formalism derivas from another one.

Actor Person, social entity or organization able to act on or exert influence on a decision. An actor has certain interest in the sytems and/or has the ability to influence, either directly or indirectly.

Agent Abstraction of an actor from the real world represented in terms of state and rules. An agent is the smallest component from the sytem and a change in the states and/or rules produce a change in the interaction structure.

State Relevant information that defines the agent. The information is represented by a set of parameters which can be private or public. In case the state is private, it cannot be observed by other, whereas public states can be observed at any time by any agent.

Rules Internal model of the agent that convert the input into outputs based on the internal states of the agent. An agent can act rationally or irrationally based on its rules.

Emergence System behaviour caused by the interaction of agents and cannot be predicted. The overall system behaviour is the result from decisions made by multiple agents in particular conditions of the environment.

Interaction Agents' cooperation and coordination which produces a coherent behaviour. The interaction is possible because of interface and protocol similarities.

Protocol Set of rules which determine the messages' format.

Interface Communication language with enables agent to understand each other.

Message Information or command which are inter exchanged amongst the agents.

Attractor Position in the state plane which represents the impossibility to change to other states.

State space Space in which all possible states of a system are represented. It represents what the system can be which might not be obvious.

Network Structure of the aggregated interactions between the agents represented by nodes and edges. A change in the intensity of connections amongst agents create a dynamic network. Modification in nodes and edges create evolution of the network.

Node Represent agents in the network structure.

Edge Interactions between nodes and appear the moment agents interact.

Pattern An organization discovered in a dynamical system in either space or time.

Tick Discrete time period in which agents interact, change states and produce a behaviour. The first tick assembles the system and does not undertake the former actions.

Part I

The Electricity Congestion Issue: From Scarce Capacity to Potential Use of Market Power

Chapter 1

Introduction

Since bottlenecks in the transmission systems cannot be eliminated in the short-term, TSOs have to apply rules which were set up by the Member States following the guidelines of the European Commission in the case of congestion. The congestion might give room for Producers to manipulate the market outcomes, and thanks to the liberalization process, take advantage of reduced control.

1.1 Background of the Investigation

The liberalization process in electricity markets

The Consumers' benefits from the ongoing electricity liberalization process are at stake. The introduction of competition is theoretically meant to increase efficiency and *reduce prices*, where this latter benefit should directly be passes to the Consumers. The liberalization process introduces competition where possible, and regulates the networks[1]. This transition was justified by changes in technology, like diminishing economies of scale in the electricity industry by introducing smaller efficient plants such as CCGT[2] power plants. The process aims to divide the vertically integrated infrastructure into generation, transmission, distribution and retailing; in other words to separate the value chain of electricity.

The vertically integrated undertaking was regionally or nationally organized in a single undertaking that generated, transmitted and distributed electricity to the final customers. All the decisions were thus done by a single undertaking. In the aim to create a competitive market, the once vertical integrated companies were and still are forced to unbundle, thus creating more interacting market players and *increasing the complexity* of the coordination in the system.

Coordination in liberalized electricity markets

Some of the most important difficulties appeared with the coordination between the technical and economical tasks in the new liberalized electricity markets. On the economic side, market players need to face market dynamics while pursuing their goals. For example, Producers seek to maximize their profit by selling electricity while Consumers aim to maximize their utility by buying cheap electricity. Electricity has to be balanced in real time, since it cannot be economically stored and so the system should be robust enough to cope with changes in generation and/or consumption or even with equipment failure. One of the most important parts of the electricity system, the transmission network, resides in the Transmission System Operator, which plays an important role in the construction of the *Internal Electricity Market* (Glachant and Leveque, 2006). According to Glachant and Leveque (2006) the purpose of the TSO is stated as:

> [...] the Transmission System Operator (TSO) should implement its three main missions to manage the flows of electricity, that is to say as for (1) the short-term management of electricity flow externalities, for (2) the development of the grid (Brunekreeft et al., 2005), and for (3) coordinating neightboring TSOs in order to deal with border effects.

Clearly the TSO must undertake technical and economical tasks. In the short-term it has to balance supply and demand, since it is impossible to precisely forecast electricity consumption (Vries et al., 2009; Knops et al., 2001). The TSO therefore manages the electricity in a network, which is basically formed by transmission lines.

Transmission lines importance

The transmission lines play an important role in electricity markets since they carry the electricity generated by Producers to the distribution network that ends up with the Consumers. In Europe, the transmission system plays an important role since one main target of the liberalisation of

[1] Since networks are assumed to be natural monopolies.

[2] CCGT stands for combined-cycle gas turbine. It operates by using gas mixed with air to fuel a gas turbine and the heat from the turbine exhaust to heat a boiler from which the steam powers a steam turbine and second generator, hence two generators function for the same fuel costs.

electricity is to create the *Internal Electricity Market* Knops et al. (2001). The *Internal Electricity Market* progressively implemented since 1999, aims to deliver real choice for all Consumers in the Community. The legislation packages[3] are expected to strengthen the EU's internal energy market, give Consumers more protection and benefit from lowest possible energy price while offering companies a competitive playing field (source European Press room, Reference: IP/09/1038 Date: 25/06/2009).

Another political goal is the *renewable share* imposed by the EU. Since the sources are far from the consumption centre, for example in the case of offshore wind, new transmissions must wheel this new flow and connect to the old transmission grid. If there is no adequate interconnection then the electricity cannot flow, and there will be no connection between countries and no future for renewable development.

Congestion in electricity markets

Congestion exists whenever the line capacity is lower than the flow found in the clearing process, in other words the line capacity *limits the optimal flow* found when matching supply and demand. Congestion can occur on a physical basis or an economical basis (Knops, 2008). The physical-congestion is the technical impossibility to meet the demand and operational measures cannot solve the problem. However economical congestion can be solved by means of operational measures, thus keeping the distribution of electricity within secure limits. In deregulated systems, the Transmission System Operator (TSO) is in charge of maintaining the acceptable level of electric power security. Among other activities, the TSO is responsible for congestion management.

Although tariffs and transmission access are regulated, there is a growing market-based pricing mechanism in transmission networks (Energy and Transport, 2004). In principle, the market will decide where to allocate the scarce resources to the market players who valuate the commodity the most. If there is electricity line congestion, the scarce resource is thus the line capacity (which limits the flow) and the market players are the electricity Producers. The transmission capacity creates bottlenecks in the network since the desired electricity flow cannot go beyond the capacity without creating a blackout risk.

The role of re-dispatching mechanism as congestion mechanism

As congestion is an imminent issue, countries must adopt a congestion mechanism. A *congestion mechanisms* is a policy which handles congestion of power lines between security levels (line flows lower than maximum line capacity). There are two types of congestion mechanisms, namely capacity allocation mechanism and capacity alleviation mechanism. The former group assigns the physical capacity of the line before the physical delivery, whereas the latter group are often

[3] The package is composed of:

- Directive 2009/72/EC of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC (OJ L211, 14/08/09)
- Directive 2009/73/EC of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC (OJ L211, 14/08/09)
- Regulation (EC) No 713/2009 of 13 July 2009 establishing an Agency for the Cooperation of Energy Regulators (OJ L211, 14/08/09)
- Regulation (EC) No 714/2009 of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003 (OJ L211, 14/08/09)
- Regulation (EC) No 715/2009 of 13 July 2009 on conditions for access to the natural gas transmission networks and repealing Regulation (EC) No 1775/2005 (OJ L211, 14/08/09)

used to relieve congestion in real-time (Krause and Andersson, 2006). As ETSO (2003) indicated, the TSOs need appropiate measures to cope with real time congestion produced by a change in day ahead forecast[4]. Re-dispatching and counter trading are the capacity alleviation mechanism which are largely being used alongside with capacity allocation mechanism[5]. Counter trading is in essence the same as re-dispatching, the difference is that the TSOs do not have the authority to dispatch generators directly and the capacity is bought in a market (Boisseleau and de Vries, 2001). The importance of re-dispatching is reflected in the fact that by 2006 the traditional power flow control[6] in the case of Belgium, France and the Netherlands, was realized by means of redispatching of generator (Meeus et al., 2006).

The importance of simulations

Despite recent achievements in the decision making process regarding energy markets, there is still a *deficit* regarding decision support for electricity market players which can only be overcome by having better modelling (Pinto et al., 2009). The relative new electricity market structure continues its design process and need insight into the strategic level of market players rather than prediction which cannot capture the dynamic, adaptation and interaction of market players. There are many different simulation approaches, which amongst them; agent-based seems to capture the particular characteristics of the electricity markets.

For readers seeking further details on agent-based modelling, I suggest you read the PhD thesis *Co-evolutionary Method For Modelling Large Socio-Technical System Evolution* elaborated by Nikolic et al. (2009).

1.2 Problem Statement[7]

Problem owner

The problem owner is the European Commission which establishes legal constraints[8] in the aim to *foster competition* while *safeguarding Consumers*. Its main concern is to pass the benefits from liberalization to customers. However, manipulation of the market caused by Producers' strategic bidding can reduce this benefit and jeopardize the success of the liberalization process itself.

The real situation

Congestion is a situation which, in general, will always exist since the line capacity is finite and takes years to increase its value while electricity demand continuously increases. With the construction of lines, the regional markets can be integrated, and so the undertaking's regional market power, in terms of market share, will be reduced. However, unbundling is preferred to increasing the line capacity to overcome the local market power (see Section 2.2). The congestion

[4]A change in load pattern, production scenarios and weather conditions may lead to congestion which was not foreseen.

[5]For example congestion in the Nordic area is managed by market splitting and counter trading NordREG (2007).

[6]After the Producers have submitted their bid position to the TSO, the TSO balances the system and manages congestion.

[7]The problem statement adopted is aligned with the definition given by Enserink et al. (2009) : "A problem is the gap between the current or expected future situation and the wanted situation as perceived by the problem owner".

[8]Regulations and Directives are legal constraints which give Member States guidelines to manage the congestion.

situation is not new, but the implications for customers and for the liberalized electricity sector need to be *explored*. In the case of congestion, the Producers might take advantage by using their market power. The producer market power exercise can be seen as strategically bid into the electricity market by either withholding output or offering higher prices than the competitive bid for the block of electricity offered Twomey (2005). This situation has already happened as the Federal Energy Regulatory Commission (FERC) concluded in its summary of findings: "Electricity prices in California's spot markets were affected by economic withholding and inflated price bidding"[9].

The wanted situation

The European Commission (EC) is keen on pushing forward the benefits of the ongoing liberalization of the electricity market, by guiding Member States to incorporate market mechanisms which reduce or avoid Producers' market power. In the short-term, the EC aims to safeguard customers by minimizing tariffs. The tariffs have different components such as transmission fees, distribution fees and electricity price. While the distribution and transmission fees are regulated, the electricity price found in the market clearing process can be manipulated by the Producers, and especially in case of congestion. The likelihood of manipulation should be minimized and the electricity price should thus be equal to the real price of electricity[10].

Gap

The difference between the manipulation of the electricity price in the case of congestion (real possible situation) and the fully competitive electricity markets (expected situation) can be compensated by incorporating sound mechanisms. This situation defines the problem statement as:

> *Provided that congestion is a recurrent problem in electricity lines; in the short-term, along with ex-ante congestion mechanism, real time solutions must secure the electricity supply of electricity while reducing or avoiding strategic bidding which reduces the liberalization benefits passed to Consumers.*

Therefore, a deeper insight into the strategic bidding process in congested lines is needed, so as to assess the robustness of the congestion mechanisms. A simulation which can give insight of the Producers' bid position can be used to reveal the possible use of market power in the case of congestion.

1.3 Research Objective, Questions and Scope

Objective The objective of this thesis is to gain an understanding of the Producers' strategic bidding process in congested lines by means of a simulation model.

Based on the objective, the main research question is:

> **(MQ) How could market power, in the case of congested electricity lines be modelled?**

This will lead to the following sub-questions:

[9] Source: http://www.ferc.gov/industries/electric/indus-act/wec/enron/summary-findings.pdf Retrieved: 2010-03-17

[10] The real price of electricity should reflect only the cost associated to generate electricity.

- **(RQ1) What are the most important mechanisms to solve congestion as seen in the European Wholesale Electricity Markets?**
- **(RQ2) What is an adequate modelling paradigm to simulate the Producers' market power?**
- **(RQ3) What is a useful algorithm to describe agent learning behaviour?**
- **(RQ4) What are the characteristics of the market players' states and rules?**

Scope of the research

The focus of this thesis is on the short-term where no investments and no technological change take place, either in transmission or generation. In this period, Producers might take advantage of Consumers by manipulating the market results. The electricity markets have been manipulated before, like in the case of California (FERC, 2001) or in Britain (NERA, 2009) when Producers gained extra profit at the expense of the Consumers when electricity lines were congested. Therefore the analysis of the system tackled in this thesis, is of high societal relevance which is a concern to the European Commission.

1.4 Research Methodology

The methodology adopted in this thesis is explained in two parts. First the general research strategy provides an overview of the steps followed to undertake the research. Second, the a detailed explanation of the research modelling process which correspond to the selected paradigm approach (see Section 3.4 for details in paradigm selection) is presented.

Research Strategy

Given that this thesis aims to analyze the Producers' bid in congested lines, it deals with the power grid, and the electricity market build alongside. Power grid, is considered to be large-scale sociotechnical systems[11] (LSTS). Many different knowledge domains are needed, in order to understand it. The complexity of the system need a sound sequence[12] of research activities translated into a research framework. The research framework, is built up with objects of the research project clustered into in a sequence of four phases as depicted in Figure 1.1.

This framework is formulated as follow:

> (Phase 1) An analysis of the relevant literature on the current congestion management mechanisms, economics and technical formalisms of congestion will define the simulation structure (Phase 2) by means of which the re-dispatching mechanisms (congestion management policy) can be evaluated. At the outset of the Phase 2, the suitable modelling approach which is aligned with the objective of this thesis is selected. Moreover, the simulation structure will be tested so as build the confidence of the expected results. The results from different experiments will be explained based on a know theory (Phase 3) and the final conclusion of the research will be performed (Phase 4).

[11] According to Hughes et al. (1987) large-scale sociotechnical systems consist of large number of diverse technical artifacts within societal systems. Different social organizations and arrangements such as policies, companies and institutions develop, colaborate and depend upon the technical parts Beers et al. (2007).

[12] In practise the steps presented are iterative, however for simplicity a linear process of the research endeveor in presented here.

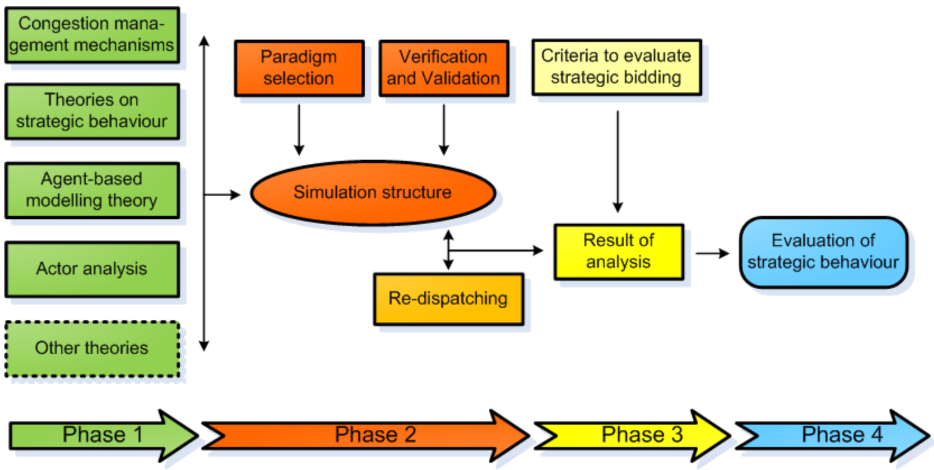


Figure 1.1: Research framework.

In each of the phases of the research framework, different methods are needed to carry the research. In Phase 1 a 'literature survey' is used to gather relevant theory which will help to construct a trustworthy and robust simulation in Phase 2; and as well define appropriate concepts to correctly assess (in the Phase 3) the model outcomes. The literature will scrutinize areas of knowledge such as economics, agent-based simulation, game theory, and current policies that tackle the congestion in electricity lines. The actor analysis will be based as well in the literature survey of relevant information and not in other methods such as interviews because the research's focus is the strategic behaviour rather than a detailed abstraction of the agent that could take a lot of time.

Phase 2 undertakes a *computer simulation* approach. *Computer simulation* is an abstraction of the real world, and is used to alter components and explore the outcomes. However in some simulation approaches, the overall structure is constraint and leaves no room for agent to interact (see Section 3.3 for further insight). In agent-based modelling, agents take their own decision by interacting among them within a common environment. As Chapter 3 concludes, Agent-Based fits with the underlying characteristics of the sytem, and will be employed in the research. The research will built a model that reflects the interaction of agent in electricity market in case of congestion. The purpose of the model is to clarify the possible use of agents (Producers) market power. The assembled model is verified and validated so as in Phase 2 the results of simulations are presented and analyzed. The analysis will assess the Producers' bid position in the both case, no congestion in lines and congestion solved by re-dispatching. In the last phase, the conclusions of the research is documented, making reference to the research objective and research question (see Section 1.3).

The Phase 2 is critical because it deals with the formalisation of the relevant domain knowledge into computer-readable language. This phase undertakes activities such as building the model and testing its suitability with respect of the research's objective. The research modelling process encompasses features of all Phases, however it be assumed that activities focus especially in tasks from Phase 2.

Research Modelling Process[13]

Electricity transmission networks are infrastructures composed of many technical artifact, such as cables, pylons, trasformers and so forth. They also consist of social components, such as policies, organizations and institutions. Thus, electricity transmission networks correspond to the large-scale sociotechnical systems (LSTS) characteristics. The process of modelling LSTS posses many challenges. These challenges are studied and may be overcome by using strategies developed in the work made by Beers et al. (2007). Basically the challenges are due to LSTS need many specialist from diverse knowledge domains are required to have a better understanding ot the system. The specialist communicate through interfaces, enabling the share of knowledge. These interfaces can be seen as:

Soft-soft

The first interface deals with the knowledge sharing amongst different knowledge domains. In the case of this thesis, the different knowledge domain needed to understand the *European Wholesale Electricity Market* system are well defined, and the modelling process starts with an inventory of the system and identification of its components. The inventory is formed by the following steps:

- **System definition:** The real world system which the research focuses is described and analyzed (see Section 5.1). The aspects and the boundaries of the system, which will be define the elements inside the system, are delineated. The system is decomposed into two coexistent layers which enclose a particular aspect of the system (see Section 5.1 and 5.1). This activity gives as result the system diagram, see Section 5.2.

- **Define the actors:** Agent-based is based upon actors abstracted into agents, so the main actors and the problem owner are identified. The position of the actors and with special attention the problem owner's position is analyzed (see Section 2.4). The underlying questions that problem owner aims to resolve through the model are determined, see Section 1.3.

- **Time frame:** The relevant period which the research focuses affects the actors' position. The time frame chosen in this thesis correspond to the short-term (see Section 5.4).

Soft-hard

This interface corresponds to the formalisation of the system understanding. The aim in this activity is to produce a shared conceptual model. In this thesis, althought the conceptual model endeavour will produce an ontology[14], it will not be translated into a language for agents. This decision is done because the system is not complex enough and the thesis has a tight time constraints. This interface is principally composed by the following activities:

- **Define the agents:** The principal agents within the system boundaries, and which interaction produces the emergent system are identified and described (see Section 5.3).

- **Formalize the agents' states and rules:** Each agent is equipped with particular states and rules. These unique set of characteristics define the agent's behaviour (see Section 6.1).

[13] The research modelling process adopted in this thesis is aligned with these strategies in order to use an agent-based approach.

[14] Ontology is a formal description of entities and their properties, relationships, constraints and behaviour which are machine-readable and machine-understandable Nikolic and Dijkema (2006). Although they are very easy to use because they require little prescribe structure Beers et al. (2007) they need a lot of time to be developed.

- **Agents' interaction:** Based on rules and states, the agent will cooperate and communicate with other agents in the system and hence interacting amongst them. The main interaction is identified and described (see Section 5.3).
- **Formalize agents' interaction:** The interaction (based on rules and states) need to be transformed into a computer-readable code in order to build a model. (see Section 6.4)

Hard-hard

Although Beers et al. (2007) mention that ontology is a starting point for construction the agent-based model, in the case of this thesis, as explained before, an ontology will not be used as interacting language for agents. The communication which the agents use is built upon mathematical code rather than a description of characteristics[15].

Aspects such as process to translate the formalized agent's states, rules and interaction into code are undertook in this interface. The model procedure and details of the software code are omitted in this thesis. However, the verification and validation test that assess the suitability and the model outcomes are presented in Section 7.

1.5 Research Roadmap

This thesis is structured into 3 Parts, 8 Chapter and 7 Appendixes; this structure is depicted in Figure 1.2 which forms the roadmap[16] of the research.

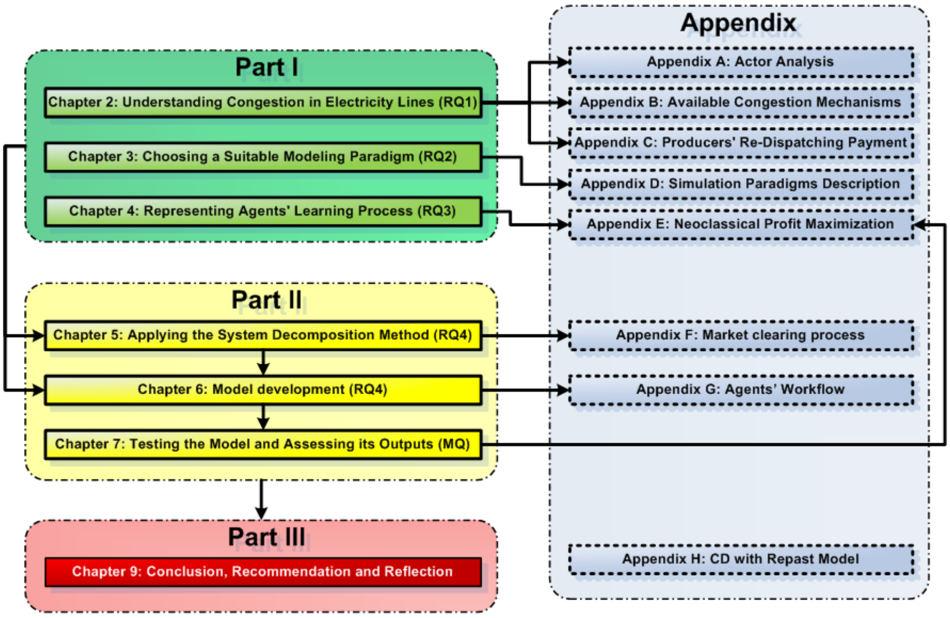


Figure 1.2: Research roadmap.

[15]For example, in the case of the bidding process the agents give a vector formed by a quantity and a price without defining what is a price or what is a quantity and so, no formal language definition was required.

[16]At the start of each new Chapter, a zoon of the research roadmap will be presented to indicate the position of that Chapter within the thesis.

The first Part introduces the reader to the congestion issues, gives some explanation of its background and outlines the need for an appropriate simulation approach to underpin the possible manipulation of Producers in the electricity market. The second part makes reference to the modelling process used and tries to represent the congestion issue into a computer-readable language to be simulated using an agent-based approach and expose the outcomes of the model. The third and last part presents conclusions drawn from the model results.

The first Part encompasses 3 Chapters. In Chapter 2 the RQ1 is answered wherein concepts regarding congestion in electricity markets and details of re-dispatching are exposed. Further detail of this Chapter can be found in three underlying Appendix. First Appendix A give the result of an actor analysis. Second Appendix B describes the available congestion mechanisms in electricity market. Finally Appendix C specifies the particular Producers payments in congested electricity lines ruled by re-dispatching. The RQ2 is being addressed in Chapter 3, which underpins the argument of the paradigm selection by first exploring alternatives and then selecting the most appropiate for the research objective. Complementary details of the most important simulation paradigms are situated in Appendix D. At the end of the the first part, Chapter 4 presents a suitable algorithm to represent agents learning, and thus, it answers the RQ3. Additional information regarding game theoretical market structures are calculated in Appendix E.

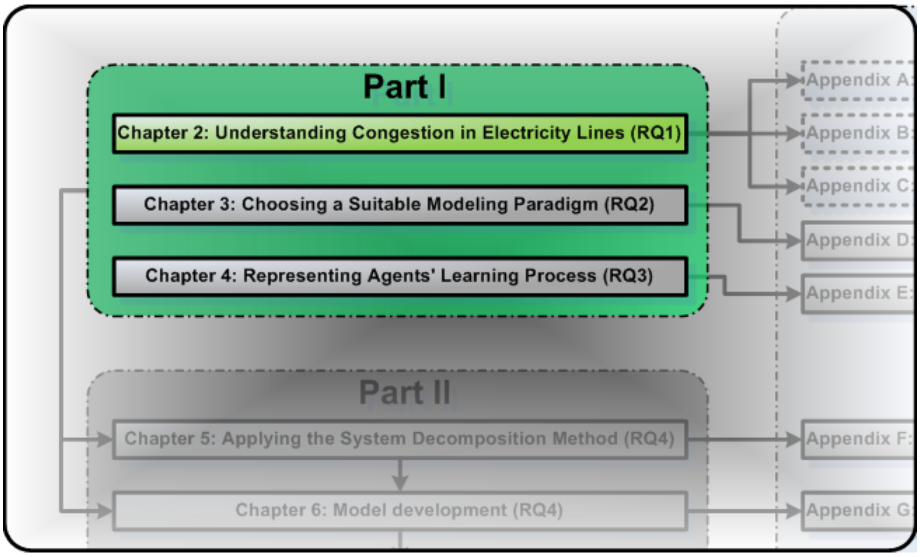
The second Part is composed of 3 Chapters. Following selection of the approapiate modelling paradigm and based on the characteristics of congestion and the agents learning process, Chapter 5 and 6 abstract the system and therefore, they both answer RQ4. Chapter 5 aims to thoroughly apply the simulation paradigm methodology and capture the system's structure. Appendix F exemplifies two cases of market clearing process which complement the explanation of Chaper 5. Chapter 6 translates the system based on the previous Chapter's outcome into a formal computer-redable language. Appendix G details the agents workflow complementing the exposition of Chapter 6. Chapter 7 will address the MQ by first providing the confidence that the model has been carefully built taking into account the guidelines of the previous Chapter and second presenting some interesting results found in the model output. This model output will be tested against theoretical equilibrium prices calculated in Appendix E.

The third and las Part is formed by 1 Chapter. The most important analysis' results and insights gained in the previos Parts will be summarized in the Chapter 8 in terms of the conclusion of the thesis, recommendations for further research and reflections of the modelling endeavour.

Along with this thesis, a CD with the models which were build on Repast is attached in Appendix H.

Chapter 2

Understanding Congestion in Electricity Lines



This chapter addresses RQ1 by exploring the underlying characteristics of congestion. The concept of congestion is explained in Section 2.1. Then an explanation of the causes (Section 2.2), the consequences (Section 2.3) and the view of the actors involved in the issue (Section 2.4) are provided. After some of the available solutions to manage congestion are presented (Section 2.5) making emphasis in re-dispatching (Section 2.6).

2.1 What is congestion?

This Section will introduce the congestion issue by providing an understanding of when and why does congestion occur.

Congestion occurs whenever there is insufficient capacity to transport electricity from one bus[1] to another. Electricity needs to be transported because the generation of electricity is generally away from the center of consumption. The electricity transport is done through transmission and distribution lines. Basically the transmission lines differ from the distribution lines in the voltage level. Transmission lines have high voltage, in comparison with distribution lines, since this is a way to reduce the loss of electricity[2]. The maximum capacity that the line can support in security level, is know as thermal power flow limit.

Thermal power flow limits[3] is the maximum flow at which the temperature in the cable do not produce damage. If the line temperature overpasses this limit, then the line will loss strength and will sag towards trees or object bellow the lines. If there is a connection between the line and the object below it, then a short-circuit appears and may create a black-out.

2.2 Causes of Congestion

This Section reveals the underlying factors which create congestion in electricity lines and exposes the position of the European Union.

The most logical cause of congestion is the lack of proper lines which could wheel the electricity from one bus to another. In other words the thermal limit of the lines, or capacity, prevents the optimal to exchange electricity amongst market player. There are a number of possible methods by which the MW thermal capacity of an existing line may be increased. Some of these methods are technically straightforward, such as reinforcing the structures and restringing the line with a larger conductor. However, these methods come at a high price and in addition the planning and construction takes several years. The construction needs special methods to allow service while the work is in progress (Doss, 2002). Assuming that demand increases through time while the required capacity to transport electricity increases in discrete amounts after certain period, congestion takes place periodically as Figure 2.1 shows.

In Europe the interconnection lines where built with the aim to enhance the stability of the system in case of emergency (Knops et al., 2001; Vries et al., 2009). Weak connections do not fully permit the trade of electricity, and thus help to create electricity prices difference between local markets or countries. Countries with relative cheap electricity prices are reluctant to connect with countries with more expensive electricity because the electricity price should be the same in both interconnected countries. According to EUROSTAT (2009) the electricity price for household customers in the first semester 2009, ranged from 8.23 [€/100 KWh] to 29.98 [€/100 KWh] respectively in Bulgaria and Denmark. The average for the 27 Member States is 16.58 [€/100 KWh] and in the case to The Netherlands is 19.00 [€/100 KWh]. The difference in electricity price can be explained by physical and regulatory constraints. For example in Germany the price is lower than in the Netherlands not only due to cross subsidization from network incomes and subsidies for lignite, but because the price-settling generator is a coal-fired plant whereas in the Netherlands is a gas-fired plant[4] (Vries et al., 2009). Therefore a large integration in

[1] Buses are points in the network where electricity from generation can be input or it can be drawn to be consumed.

[2] The idea is to reduce the current, since $P = VI$ (where P is power, V is voltage and I is current) to have the same power, with lower current, the voltage have to increase.

[3] Thermal power flow limits usually determine the maximum power flow for lines less than 50 miles in length.

[4] The gas prices are indirectly affected by oil prices currently in increase. On May 2010, the price was 75$/barrel

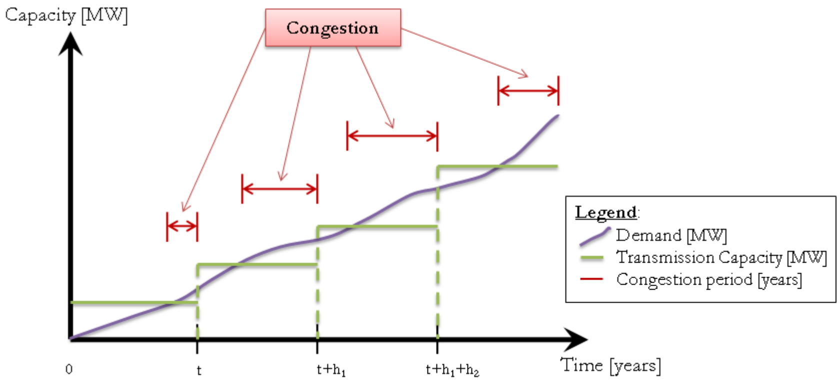


Figure 2.1: Capacity and demand development

Eurpe, might result in high reluctance from countries where electricity is relative cheaper with respect the other Member States[5]. This lack of integration implies that isolated markets can be manipulated by Producers who have local market power. Producers can set high prices because cheap electricity cannot arrive to the local market given the limited interconnection capacity.

With reference to the European Union, one solution to overcome local market power is to build more interconnection capacity between Member States. However this might not be an economical solution given the amount of time and cost to built network capacity with comparison to unbundling an incumbent. Therefore in economical and implementation terms, the interconnection capacity is a second efficient way to raise competition in the European Union since unbundling is preferred to overcome the local market power (Vries et al., 2009; Knops et al., 2001; Knops, 2008).

Table 2.1 presents the frequency of congestion between the most important electricity markets[6] in Europe from 2003 to 2006. It can be seen that in mayority the conections were congested.

Table 2.1: Congestion frequency (Bosco et al., 2006).

Export	Import	Congestion Fequency
Powernext	EEX	frequently
EEX	Powernext	never
EEX	APX	frequently
APX	EEX	seldom
EEX	EXAA	never
EXAA	EEX	never
Nord Pool	EEX	frequently
EEX	Nord Pool	occasionally

and the forecast was 85$/barrel in 1 year time. http://www.oil-price.net/

[5]If The Netherlands were fully interconnected with Germany, France, Belgium, France and Denmark (taking into account present and future interconnection proyects); and assuming large enough capacity, the average price in the region would be 19.26 [euros/100 KWh]. This implies that The Netherland would varely see a change (around 1 %) but Denmark would feel a decrease of almost 30%, whereas France would experience an increase of almost 50%.

[6]These markets are Powernext, EEX, APX, EXAA and Nord Pool. Powernext is the French energy exchange; EEX is the German energy exchange; APX is the Anglo-Dutch energy exchange; EXAA is the Austrian energy exchange; and Nord Pool is the single enegy market for Norway, Denmark, Sweden and Finland.

2.3 Consequences of Congestion

This Section illustrates the effect of congestion over the European Union's goal to create the internal market in electricity and safeguard Consumers. Moreover, an example illustrates a case of congestion between two power markets.

Transmission plays an increasing vital role in the modern electricity system since they bridge Producers with Consumers. Electricity flows throughout transmission lines dictated by physical laws rather than contract paths. This means that we cannot freely trade electricity but we need to take into account the flows which result from this trades. Congestion may prevent the existence of cheaper electricity contracts because the net flow of the trade could put in risk the line. Therefore, congestion will create a price difference between local markets (poorly interconnected) and in the case of the European Union; congestion hampers the creation of the internal market in electricity.

Example of Congestion in Two Zones

As analyzed before, price difference may result in some countries reluctance to increase the electricity lines capacity, and thus local markets will be isolated. The Figure 2.2 presents an example of two interconnected zones with a limited capacity. The transmission line has a maximum capacity of P_{ab}^{max}. In zone A Producers facilities with low cost are located, whereas in zone B there are mayor Consumers.

Producers and Consumers bid in each zone represented by P_G^A, P_D^A,$P_G^B$and P_G^B; where G stands for electricity generation from Producers and D means the Consumers' demand. With no congestion, the market will be cleared at the single electricity price p_u (left graph). If $p_u > P_{ab}^{max}$, then the line is congested. In the case of taken market splitting as congestion management mechanism, the markets must be split into the zone A and B. The market operator will buy electricity from the zone A and sell it to the zone B. Thus the demand in zone A will be equal to: $P_{Dnew}^A = P_D^A + P_{ab}^{max}$, whereas in zone B we will obtain: $P_{Gnew}^B = P_G^B + P_{ab}^{max}$.

The result of the procedure gives p_a as the electricity price in zone A and p_b in zone B. Note that $p_a < p_u < p_b$, so Consumers in zone A pay a lower price than in the case of no congestion, whereas Consumers in zone B pay a higher price than before. Conversely, while Producers in the zone A receive a lower income in comparison with the case of no congestion, Producers in the zone B get a higher income with respect the case of no congestion. If the maximum capacity P_{ab}^{max} were lower, then the difference in prices will be higher, since the market operator would not be able to trade electricity between the zones.

According to Vries et al. (2009); Knops et al. (2001), one of the main physical obstacles to the integration of electricity markets is congestion of interconnectors. At European level, the congestion of interconnectors between Member States, hindering the creation of an authentic Internal Electricity. Moreover, the limited capacity isolate local markets in which Producers can exercise market power or not improving their efficiency since a limited competition is possible (competition in the sense that Producers outside the local market could offer their electricity).

2.4 Multi-Actor Analysis

With a deeper understanding of congestion gained in previous Sections, this Section acknowledges the main actors which are involved in the congestion issue; enlighting their objectives and instruments.

The congestion problem at the European level is a complex multi-actor problem. The European Commission is not the only or an isolated actor in this matter. He is part of an intertwined

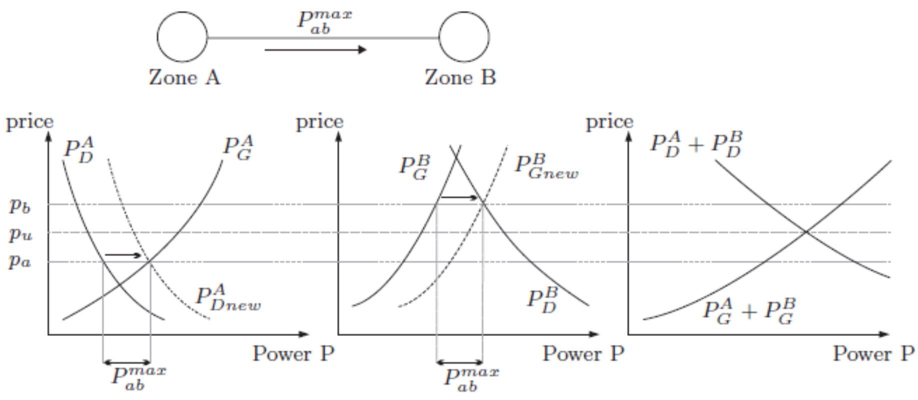


Figure 2.2: Two zone price area example (Christie et al., 2000).

network, in which many actors have different interest or despite their common interest, their opinion the problem, the cause and the solution may be different (see appendix A). The main actors who directly or indirectly influence the problems were identified based on the positional approach[7]. They were grouped based on their core interest into two categories, namely *public interest* and *private interest* as table 2.2 shows.

Table 2.2: Groups of actors involved in the system.

Group	**Actors in the group**	**Group's objective**	**Group's instruments**
Public Interest	• European Commission • Regulatory Authority • Consumers • Transmission System Operator	Consumers protection	• Directives and Regulations • Claims to authorities
Private interest	• Producers	Higher profits	Strategic bidding

Within the public interest group, the actors have different objectives and means, but as a whole they share the underlying goal to safeguard the customer in terms of electricity price that they pay. This means that the tariff billed to the customer, should reflect the real price of electricity production[8]. The European commission through the Directives and Regulations set guidelines to manage the congestion that the Regulatory Authority must comply.

[7]The positional approach reviews the existing policy making structure identifying actors with formal position in policy making.
[8]The price should cover only the electricity production cost and not extra-profits.

2.5 Available Solutions

This Section makes evident the large amount of available solutions and demostrates the importance of re-dispatching.

As indicated before, congestion is a imminent issue, and the obvious way to solve it is to increase the connection capacity. However the cost associated and the long construction periods, hampers its implementation. As Vries et al. (2009) noted:

> [...] interconnection investment is only rational when it is a cheaper option of providing certain customers with electricity than building generation capacity locally, or where the benefits of increased network stability and security of supply outweigh the costs.

In the short term the lines' capacity will not be increased, but congestion has to managed. In principle, congestion mechanisms can be clustered into two groups, capacity allocation and capacity alleviation (consult Appendix B for detail of these congestion mechanisms). While capacity allocation mechanism allocate the line's capacity before the generation of electricity, capacity alleviation mechanisms are referred as remedial actions (Krause, 2007). Alleviation mechanisms may be used in real time markets if congestion has to be relieved immediately or in markets in which no allocation mechanism is used. Basically there are two alleviation mechanisms, counter trading and re-dispatching. In principle re-dispatching is the same as counter trading, with the difference that in the latter the Transmission System Operator (TSO) enters into a market to buy electricity, whereas in the former the TSO directly orders Producers to curtail or increase their generation. However, as de Vries (2001) indicated re-dispatching is vulnerable to strategic manipulation by market players since some generators realize they have a reliability must-run (RMR) units.

RMS are power plants that are necessary during certain conditions in order to secure the operation of the network system (Didsayabutra et al., 2002). For example, in case of congestion, the TSO has no other option than to increase or start up some power plants that might be more expensive than others to reduce the flow in some lines which passed the security limit. Unforseen events can occur any time, thus even countries which select an allocation method[9] must incorporate an alleviation mechanism as well to secure the supply of electricity.

2.6 Re-dispatching Mechanism

This Section goes deeper in the detail of re-dispatching by first providing the principles to calculate that Producers receive when re-dispatching is applied in event of congestion.

If the electricity market is using re-dispatching to manage congestion, the supply (Producers) and demand (Consumers) is freely traded without considering lines' capacity which connect suppliers to demanders (de Vries, 2001; Boisseleau and de Vries, 2001). The result is planned electricity flows which might exceed the lines' capacity of the network. This implies that may be at least one flow surpasses its line's capacity (see Section 2.1 for insight of congestion) which could trigger a black-out in the network. To prevent his from happening, the Transmission System Operator (TSO) needs to co-ordinate the shifts of power plants (re-dispatch) up to the point the flow matches the line's capacity. Because of this modification in the electricity generation,

[9]The solution used to solve congestion varies from countries to country. For example in Scandinavia, Norway has a different perspective to manage congestion from Sweden and Finland. While Norway splits the system into price areas at predicted congestion bottlenecks, Sweden do not use price are to control congestion since on its perception the transmission and the market should be independent (Christie et al., 2000).

the TSOs reimburses Producers which are re-dispatched, and obtains a reimbursement from the curtailed Producers for their avoided generation costs (Boisseleau and de Vries, 2001).

An Re-dispatch example

Assume the following conditions:

- There are 5 power plants P_i, P_j, P_k, P_l, and P_m (ordered in increasing bid price).
- The plants who are inside the merit order are P_i, P_j and P_k, whereas P_l, andP_m are outside as Figure 2.3 depicts.
- P_i, P_j and P_k are causing the congestion in a given line.
- The unique auction gave as result M_3 as the market price and Q_0 as the market output.

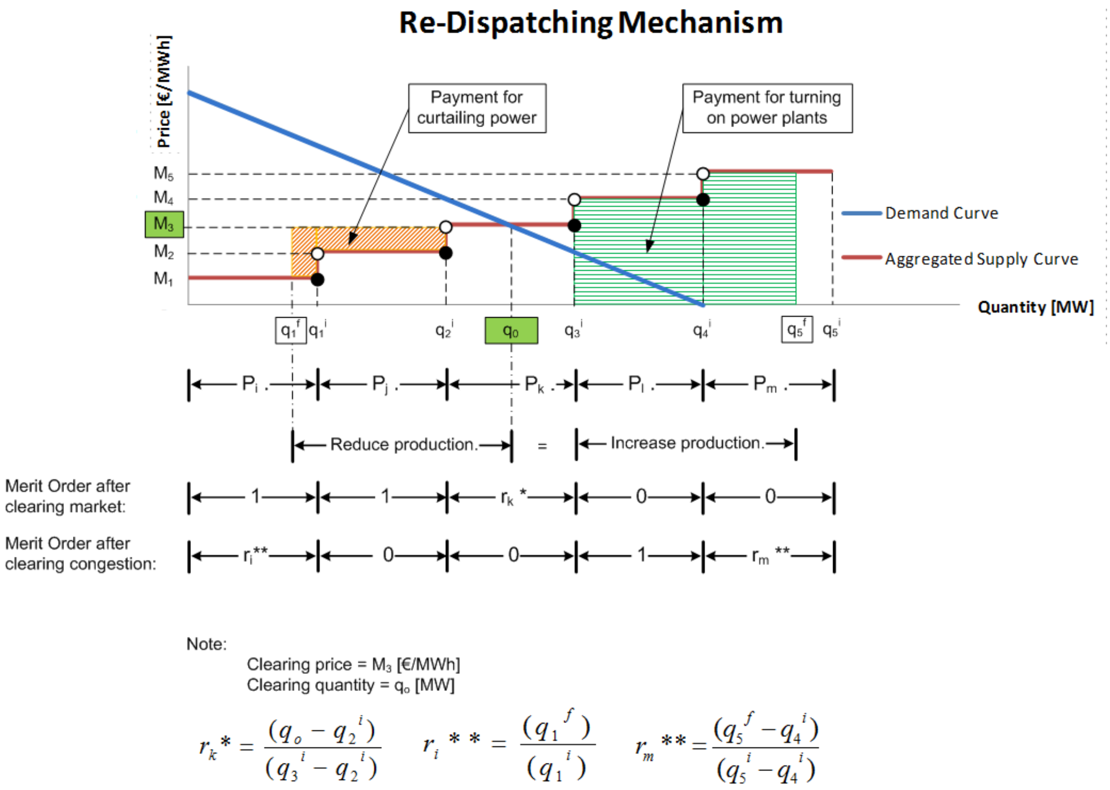


Figure 2.3: Re-dispatching producer profit calculation

The TSO has to reduce the power of plants P_i, P_j and P_k and increase the power from plants P_l, and P_m to alleviate the congestion (see Section 5.1 for further detail on flow calculation). Amongst P_i, P_j and P_k, the most expensive power plant is P_k, so the TSO curtails its output. In this case that the reduced capacity needed (to alleviate the system) overpasses the production of P_k, then the TSO will go to the next most expensive power plant. In this example, the TSO has to go until P_i, this means that P_j and P_k do not generate electricity at all and P_i partially

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generates electricity. But all reduced capacity needs to be replaced by other power plants which production do not congest the line.

In this example, those power plants are P_l and P_m. Now the process is in the other way. The TSO now seeks the cheapest power plants. If the needed increase in production is higher the the maximum output of this power plants, then the next cheapest power plant will re-dispatched until all reduced capacity is being replaced. Thus, although there is a swift of power plants, the overall production is the same and the Consumers have the amount of electricity they aim. However, there is an extra cost for this process.

This swift of generation involves two costs, the cost to start power plants which were outside the merit order (P_l, and P_m) and net payments to the generators which avoided to generate electricity although they were in the merit order. These payments are represented by the green and orange areas in Figure 2.3 respectively.

Since the bid reflect the williness of a particular Producer to produce a block of electricity in terms of money, the green area is its bid price times output. Note that the bid position is higher than the market price (corroborated by the fact that Producers are outside the merit order) but the TSO has to pay this price (as it represent the Producer position).

In the case of the Producers inside the merit order, the Producers have to reimburse the money that would have incurred if they had generated electricity. Therefore, the net payment that these Producers receive, is the difference between the market price and their bid price position. Note, that these Producers receive money without producing electricity. The total cost of shifting the electricity production is presented in the Table 2.3.

Table 2.3: TSO payments done to Producers after clearing the market and congestion.

After clearing the market			After clearing the congestion	
Producer	Generate electricity?	Payment	Generate electricity?	Net Payment
P_i	Yes	$M_3 \cdot q_1^i$	Partially	$M_3 \cdot q_1^f + (M_3 - M_1) \cdot (q_1^i - q_1^f)$
P_j	Yes	$M_3 \cdot (q_2^i - q_1^i)$	No	$(M_3 - M_2) \cdot (q_2^i - q_1^i)$
P_k	Partially	$M_3 \cdot (q_2^i - q_0)$	No	0
P_l	No	0	Yes	$M_4 \cdot (q_4^i - q_3^i)$
P_m	No	0	Partially	$M_5 \cdot (q_5^f - q_4^i)$

From the Table 2.3 we can conclude these important facts.

- After clearing congestion:
  - Producer P_i receives money for both, electricity generation $M_3 . q_1^i$ and not for avoiding to produce electricity $M_3 \cdot q_1^f + (M_3 - M_1) \cdot (q_1^i - q_1^f)$.
  - Producer P_j does not produce electricity, but it still receives $(M_3 - M_2) \cdot (q_2^i - q_1^i)$.
  - Producer P_k does not produce electricity, and it does not recieves any payment.
  - Producer P_l produce electricity, but it still receives $M_4 \cdot (q_4^i - q_3^i)$. And M_4 is higher than the market price M_3 .
  - Producer P_m produce electricity, but it still receives $M_5 \cdot (q_5^f - q_4^i)$. And M_5 is higher than the market price M_3 .

2.7 Chapter Conclusion

In general congestion is a periodic problem which we have to deal with. In the long-term the problem can be solved by increasing line capacity. However this solution need a long period of planning period and is capital intensive. Moreover, in some cases, countries do not want to increase the interconnection capacity with neighbouring countries, since this might increase their local electricity price or the cost incurred do not justify the potencia benefits.

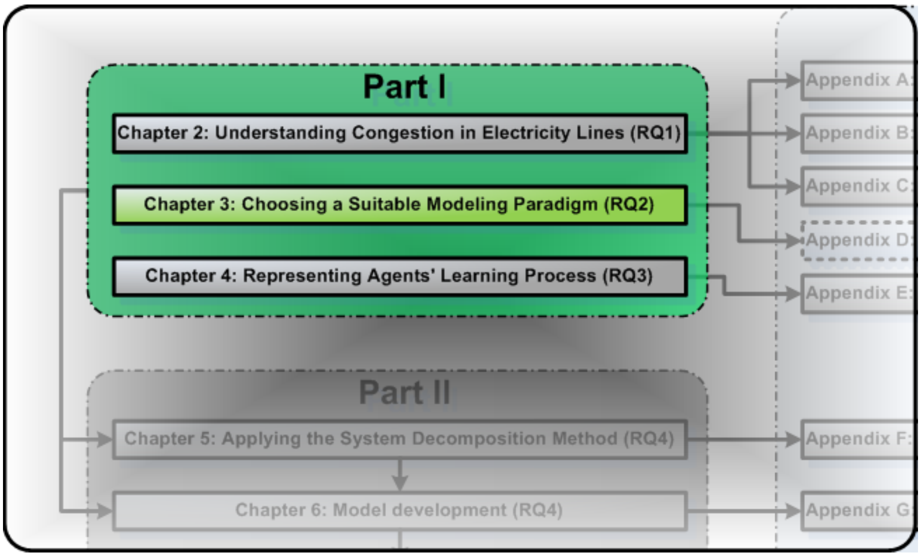
In the case of the European Commission, congestion hampers one of its policy goals: the formation of the internal market in electricity. Given the difficulties to solve the issue in the long-term and the relevance to integrate local electricity market in the Europe Union, short-term methods are needed to manage congestion. By managing congestion, it is meant to allocate the scarce resource, i.e. the line capacity connecting the electricity markets.

Independently from the selected method, Member States should adopt an alleviation method (remedial actions). An alleviation mechanism, or real-time method, alleviates congestion modify the generation load patterns after the market clearing process. It can be used in real time markets if congestion has to be relieved immediately or in markets in which no allocation mechanism is used. Re-dispatching and counter trading are two alleviation mechanisms, from which counter trading is essentially the same as re-dispatching.

Re-dispatching is thought to be vulnerable to strategic manipulation by market players since some Producers may realize they have a reliability must-run (RMR) units. RMS are power plants that are necessary during certain conditions (like in the event of congestion) in order to secure the operation of the network system. In re-dispatching, the power generators are shifted, to obtain flow below the maximum line capacity. This modification of electricity generation comes with a high cost, since curtailed and dispatched Producers are paid. While curtailed Producers are paid to avoid to generate electricity which could produce flows above security limits, dispatched are paid for replacing the curtailed of electricity.

Chapter 3

Choosing a Suitable Modeling Paradigm



In this chapter the most appropiate simulation paradigm is selected, answering the RQ2. The particularities of the system are explored in Section 3.1. Given these particularities, Section 3.2 argues the importance of a simulation to understand the system. Possible approaches are briefly presented in Section 3.3. The simulation which is aligned with the system characteristics is selected in Section 3.4.

3.1 System Characteristics

This Section inspects the characteristics of electricity markets.

The *European Wholesale Electricity Market* (see Section 5.2 for the definition of the system) is regarded as a *Complex Adaptive System* (CAS). As John H. Holland (Waldorp, 1992) stated, a Complex Adaptive Systems is:

> [...] a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents.

Thus CAS is the results of multiple agents interaction. CAS has particular characteristics, which are found in the case of the *European Wholesale Electricity Market*, namely:

Co-evolution The actions taken by any functional component affects the other ones. This means that electricity market players vary, reproduce and adapt to changes. For example an increase in production efficiency on one producer has a direct effect on all other producers with which it shares the market because if the other producers do not raise their efficiency, they will lose competence.

Intractability The co-evolutionary process cannot be predicted. For example, with the implementation of payment to alleviate congestion in California, some actors took advantage and manipulate the market result to make extra profit. If this result had been foreseen beforehand, some action would have been applied to avoid this situation.

Path dependent The decision made in the past restrain the set of possibilities in the present. The fact that the liberalization of the market has been adopted in European Union, reduces the set of possible policies to solve issues such as congestion. As well, the technologies used, mostly dependent on indigenous fuel within a country and the sunk cost on past investments.

Heterogeneity There are many different actors involved in the system. Some actors aim to meet different objectives (see Section 2.4), and even in a group of agents, there is no homogeneity. For example in the set of producers, each one might have different production cost as result of the technologies chosen and investments in innovation.

Dynamic The relation, state or rule changes thought time as consequence of modification in the environment and on the interaction amongst agents. For example, the liberalization process is not static, it undergoes changes based on feedback information of the market results.

Specific Actor Perspective The actors involved in the European electricity market have different interests, objectives and perspectives (see Appendix A). Their understanding of the market function differs steered by their interest and objectives in the issue, and thus the congestion problem will be seen differently.

As Vries and Correlje (2010) concluded, the different electricity markets can be explained from the differences in policy objectives, the path dependence of power sectors and specific conditions of each country. The introduction of climate change in policy objectives, like for example CO_2 emissions trading, create dynamic relations.

Based on the previous characteristics, the *European Wholesale Electricity Market* system is confirmed to be a CAS. The understanding of the system requires techniques which can capture the complexity and deal with the system's nature. Simulation is a promising alternative which offers the possibility to explore these systems.

3.2 Why Simulate?

This Section sustain the importance of simulation for the understanding of a Complex Adaptive System.

The understanding of a particular aspect or state in the real world can be, in general, studied undertaking an analytical theoretical models or computer based simulation. Analytical theoretical models, or static models, usually algebraic in form, have the advantage of rigour and completeness. However to make them analytically tractable strong simplifying assumptions are generally taken (Economics, 1999) and sometimes an analytical solution does not always exist, or may be hard to find (Borshchev and Filippov, 2004). Computer based simulations, or dynamical models, imitates certain key feature of the real world in computer code. The rapidly increasing computer capability eases the calculation and hence more complexities of the actual system can be studied than in the case of using theoretical models. However, it may be more difficult to determine when equilibrium has been found (Economics, 1999) and determine patterns in the results. These tasks are taken by the human researcher, who based on theory and experience, interprets the results. Based on the previous Section that the system is a *Complex Adaptive System* and vast theory along with previous researcher's experience, the computer based simulation is chosen.

Simulation modelling is a way of solving problem that occur in the real world and it is applied when prototyping or experimenting in the real system is impossible or expensive (Borshchev and Filippov, 2004). The military services were among the first to use simulation analysis, and simulations ranging from evaluations of maintenance policies to large scale war games are routinely used to guide defence policy. As Shannon (1975) stated:

> Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of a system.

Another point of view is given by Perrons and Platts (2006) who declared:

> Simulations are not tools to predict the future. Rather, they are virtual worlds or microworlds in which managers can develop decision-making skills, conduct experiments, and play.

Simulation can be seen as modelling laboratories in which experiments of the world can be performed. Simulation is rapidly growing in popularity and examples of successful simulation applications are found in a vast range of fields (Thesen and Travis, 1989). The increasing use of simulations is fostered by the constantly improving computer capabilities, and because other methods do not work for complex systems (Madachy, 2008). In the case of congestion, as Twomey (2005) suggested, simulation can be used for the purpose of ex-post comparison with actual market outcomes or ex-ante simulations of possible market outcomes given a particular market structure. In particular, Harbord and McCoy (2000) stated:

> The first task of a market designer is to ensure that opportunities for manipulating prices are eliminated, or at least reduced to an absolute minimum. Early experiments or market simulations should be primarily aimed at identifying any such opportunities for market manipulation which may have survived critical scrutiny. It is a hopeless exercise to test for stable or 'steady state' market behaviour while opportunities for outright manipulation exist, although this is what the experimenters employed by the regulator thought they were doing. Where one trader has gone, many will soon follow. Far from converging to a 'steady state', market behaviour will eventually be dominated by the 'manipulators'.

The relatively new electricity markets are complex, and its designs is in constant progress and designers still have a lack of proper decision support tools (Pinto et al., 2009). A better understanding of how new arrangements would work in practice, can be assessed with the use of simulation tools. Simulation can be an effective tool for discovering surprising consequences of simple assumptions. However, there are different types of simulation approaches which can be used based on the research's objective and the system conditions.

3.3 Available Simulation Paradigms

This Section explores the most important simulation paradigms which could be aligned with the system characteristics and the objective of this thesis.

The simulation style affects the way the aspect the research from the real world is represented into the models and its interpretation. A paradigms is regarded as a set of fundamental assumptions (implicit or explicit) regarding the key aspect of the world which wants to be abstracted into a model. There are many different types of paradigms, however as Borshchev and Filippov (2004); Nikolic et al. (2009) suggested, the main suitable paradigms[1] to analyze a *Complex Adaptive System* such as the *European Wholesale Electricity Market* are: System Dynamics (SD), dynamic systems (DS), discrete-event modelling (DE) and agent-based modelling (AB).

SD is less concerned with detail than DE or AB and focuses, how the system structures (of the aggregated entities) affect system behaviour. Individual behaviour is hard or even impossible to capture with DE and in the case of SD the behaviour is generalized. In the case of AB every agent has its own set of states and rules (which steer the agents' behaviour) which can make him different since thought the simulations, states might be modified. In comparison with SD and DE, in Agent Based, the global system behaviour is not defined, but is the emergence of interactions. While SD aggregates the behavious in a central variable, AB assigns individual behaviour and observes the emergent behaviour out of the interaction of a population of those agents (Nikolic et al., 2009). SD and AB are qualitative analysis methods, which uses quantitative modelling to analyze the information out of the model. The choice of a suitable simulation approach is essential for the success of the research endeavour. The proper approach must suit purpose and research's objective.

3.4 Why Choosing an Agent-Based Approach?

This Section establishes the most appropiate simulation paradigm which best suits the system characteristics and the objective of this thesis.

The selection is based on the nature of explanation and insights of the method. The suitable modelling approach will be selected using the framework mention by Lorenz and Jost (2006)

[1] Appendix D describes the different paradigms.

who stated that a suitable modelling approach should be found based on the best fit of the three dimensions: purpose, object and methodology; rather than taking into account technical and conceptual differences. Figure 3.1 presents the comparison of Agent-Based modelling, System Dynamics and Discrete-Event simulation based on the framework.

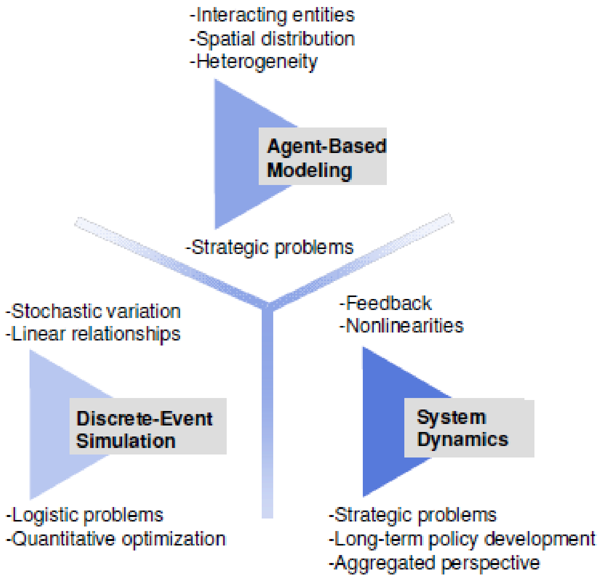


Figure 3.1: Comparison of different simulation approaches (Lorenz and Jost, 2006).

Purpose Regards the motivation of the modelling endeavour and the type of answer sought for the research question. Aspects such as insight into the problem, gaining understanding, optimizing values, reproducing a certain system and so forth, are examples of modelling objectives. In short, purpose ask the question: ***WHY?***

Object Identifies the context of the system under investigation. Characteristic of the system such as: continuous or discrete system behaviour, amount of relevant entities, relevance of interaction, differentiability of entities, and so forth. Basically answering the inquiry: ***WHAT?***

Methodology Consists of the particular methods and/or techniques of the approach. The methodology has to be chosen in correspondence with the real world objects and the purpose of the modelling. It gives the perspective of the approach (top-down vs. bottom-up), main source of dynamics (feedback or interaction of agents), validation techniques and so forth. Methodology raises the question: ***HOW?***

The objective of this thesis is to gain an understanding of Producers' bid in case of congestion (see Section 1.3). This correspond to undertake strategic insight rather than optimizing the system. Therefore, based on the purpose axis, System Dynamics (SD) or Agent-based modelling (AB) seem proper approaches.

Reductionism and holism are needed to fully understand the system. While reductionism aims to provide a detailed analysis of the components and their interactions, holism tries to describe the system in an aggregated manner. AB attains both, holism and reductionism.

AB can abstracts the system into a vast range of level (micro, meso and macro) , whereas SD focuses in the macro level (see Figure D.1). As Beers et al. (2007) pointed out, agent-based do not a priori impose model structure, but it emerges from agents' interaction. AB corresponds with the idea that the market is the final result of coordination and cooperation of agents [2]. With reference to the individual parts of the system, i.e. the agents, SD aggregate them and generalize their behaviours, whereas AB provides particular characteristics which can change with the interaction or with the inputs into the system. Moreover, the structure assumed in SD is fixed, whereas in AB the model can be constructed without the knowledge about the global interdependencies, instead the global behaviour emerges from the interaction of the individual participants.

It seems that AB is able to capture more real life phenomena in electricity markets that SD according to the research perspective. This does not mean that AB can replace SD. However on the basis of the purpose, objective and the approach methodology, AB suit the objective of this thesis and hence it will be used in the simulation of the *European Wholesale Electricity Market* system (see Section 5.2 for further detail of the system).

3.5 Chapter Conclusion

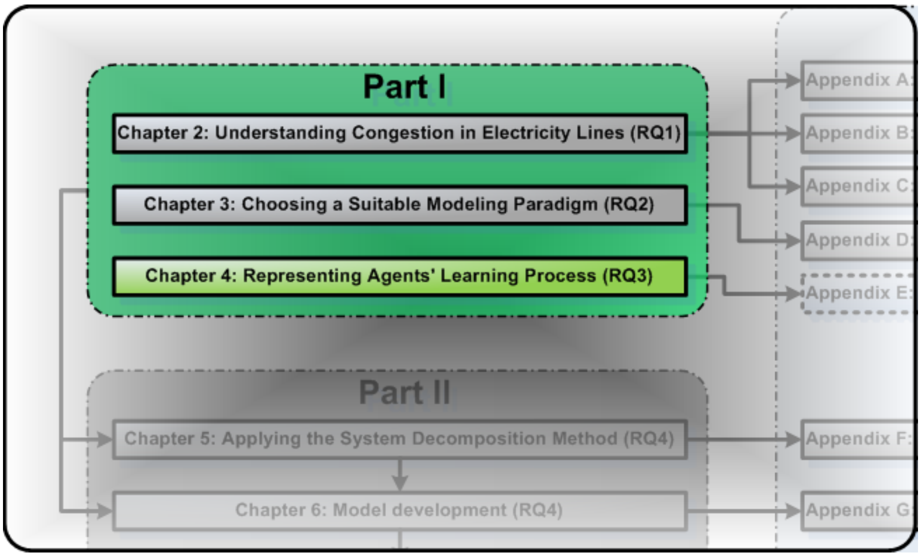
The system is regarded to emergence from market players' interaction (*Producers*, *Consumers* and the *Transmission System Operator*) who cooperate and coordinate the trade and transmission of electricity. This thesis is interested in possible exercise of market power by Producers who submit their bids taking advantage of congestion in the network.

Amongst the possible paradigms which can give an understanding of the strategic bidding in the case of congestion, Agent-Based is selected since the attributes of the system correspond to the characteristics which agent-based can deal with. As well agent-based permits the study of the market players' bids based on a learning process. Agent based focuses on the Agents' states and interactions, which are aligned with me objective of this thesis, i.e. get an understanding of the strategic bidding in congested lines.

[2]The agents are abstraction of the market players, and in this thesis they are: Producers, the Transmission System Operator and Consumers (see Chapter 5 for further detail).

Chapter 4

Representing Agents' Learning Process



The following chapter undertakes the RQ3. Section 4.1 presents principles of game theory applied to electricity markets. Section 4.2 defines what market power is, and the link with strategic bidding. Then Section 4.3 present some possible learning algorithms which represent strategic bidding. The selected algorithm is described in Section 4.4.

4.1 Strategic Bidding in Electricity Markets

In this section, the idea of strategic bidding will be presented. First notions of game theory are presented followed by possible electricity market arrangements.

In principle a well-designed electricity market should not have loopholes which can be exploited and no scope is left for gaming that jeopardizes the operation and/or distorts prices (David and Wen, 2000).

In a perfect competitive market, market participants cannot influence the price of the electricity with their output so they are price takers. In general electricity markets cannot follow this definition. Instead, electricity markets are more similar to oligopolies[1] where producer can influence the price of electricity; hence they are price settlers rather than price takers. Each Producer's objective is to maximize its own benefit in terms of profit given its own generation cost, constraints of the network and anticipating its rival reaction and hence optimizing its position (Wen and David, 2001). In other words, Producers construct its bid position maximizing its profit through strategically bids. David and Wen (2000) claimed that:

> When a generator bids other than marginal cost, in an effort to exploit imperfections in the market to increase profits, this behaviour is called strategic bidding.

Since the objective of Producers is to maximize its own position, they will take advantage of the market if there is an opportunity. Market designers need to be aware of this possible situation and foresee any potencial manipulation of the market.

Game Theory Applied for Electricity Markets

Traditionally game theory has been adopted as framework to analyze strategic interaction among players which are perfectly rational achieving equilibrium (Erev and Roth, 1998). By means of game theory, conflict and cooperation situations can be analyzed (Straffin, 1993). In electricity markets, Producers have to compete amongst themselves, but some collusion is not unrealistic though legally penalized. So it seems a good starting point to represent the strategies that Producers might use in terms of game theory.

According to the definition presented by Straffin (1993), and in the case of electricity markets, a game is composed of:

1. **Players:** Entities that cooperate and/or conflict with other entities. In the case of electricity markets, these players are Producers, Consumers and the Transmission System Operator[2]. However, in this thesis as stated in Section 5.3 only the Producers are active entities who react to past outcomes, whereas Consumers are passive entities which do not react or change their demand.

2. **Strategies:** Actions which a player can follow in order to achieve an objective. For electricity markets, Producers[3] try to maximize their profits, while the Transmission System Operator tries to minimize to generation cost or maximizes the total welfare[4]. The Producers adopt a given strategy when they bid into the electricity market and consist of the couple price and output (maximum capacity Producers can generate). The strategy is either bidding up or down with respect of its past price-bid since output is fixed (see Section

[1] The particularitites of electricity sector, such as large investment cost; legal barriers to entry; real time balance between generation and consuption; and so on, restrict Producers to entry into the market.

[2] In the case that the Transmission System Operator undertakes market and network management duties.

[3] Albeit in real markets Consumers try to maximize their utility, for this thesis they are assumed to be passive entities with a constant demand given the short term focus.

[4] The total welfare is the sum of Producers and Consumers welfare.

4.4 for further detail). The transmission System Operator's strategy is to clear the market by allocating the cheapest generators (owned by a Producer) to the Customers who value it the most.

3. **Outcome:** Final situation after a player undertook a strategy. If a Producer bids a price which is much higher than its rivals, it might be outside of the merit order. On the other hand, if it bids lower than its variable cost and is inside the merit order, the cost of production will not be recovered giving a negative profit. The merit order, electricity price and output are determined by the Transmission Systems Operator (see Section 5.1 for further detail).

4. **Payoff:** Numerical result associated with an outcome for each player. Since Producers' strategic is steered by profit, their payoff is defined to be their own profit. For the Transmission System Operator the payoff is the total cost of meet Customers demand with the electricity supplied by Producers.

As mentioned before, electricity markets resemble to oligopolies. In order to understand an oligopoly structure, first the notion of perfect competition and monopoly should be briefly introduced.

- **Perfect Competition:** The conditions requisite to perfect competition are met when Producers cannot influence on the market price. An additional condition is that all the Producers must have perfect information on the market outcomes, which is to saying that the market is transparent. The conditions guaranteeing perfect competition are not usually in place in real electricity markets, where normally only a few large producers operate. Moreover, consumer behaviour is very inelastic to price, i.e., demand is very nearly vertical since consumers don't take the price of electricity into account when deciding on whether or not to consume it. Nonetheless, it is interesting to study market behaviour under these circumstances for subsequent comparison to the conditions prevailing on imperfect markets.
  In perfect competitive markets, Producers bid their marginal cost (see Appendix E for calculation details).

- **Monopoly:** Before liberalization arrived to some electricity markets, it was the responsibility of only one vertically integrated company to provide electricity in one region. This gave no room for competition, and even though the incumbent had the network assets it could restrain the entrance of competitors. Furthermore, the assumption was that economies of scale[5] will reduce the electricity price and no competition was needed, hence monopolies were established in local markets.
  Market equilibrium in the case of a monopoly is obtained by analysing the problem of optimising monopolistic activity, which is tantamount to maximising profit (see Appendix E for calculation details). The price in case of monopoly is much higher than the marginal cost like in the case of perfect competition. Therefore, a monopoly has an extra-profit.

In perfect competitive markets and in monopolistic markets, companies can make their decisions without taking account their competitors. In an oligopolistic market, however, each generating firm must bear in mind the interdependence between its decisions and the decisions of all other market players.

[5]Where economies of scale exist, average costs drop as the size of production plants increases, which means that only companies with large-scale production centres are cost-effective.

- **Oligopoly:** Wholesale markets for electric power usually comprise a short number of large Producers, and so the structure is an oligopoly. The interdependence between Producers, influence the decision each Producers might take.
  The simple case of an oligopoly is a duopoly[6]. Therefore the problem is now to decide how much a Producer should bid taking into account the other Producer. These two traditional model of duopoly are:
  - **Cournot Competition:** Producers choose their levels of output. Equilibrium is reached when each Producers's output constitutes an optimal response to the quantities produced by its competitors. At equilibrium, no company can earn more profit if it unilaterally alters its output. To find Cournot equilibrium, the problem is expressed in terms of each Producers' optimization, in which the objective function consists in maximizing each Producers' profit (see Appendix E for calculation details).
  - **Bertrand Competition:** Producers choose prices to sell their output. Producers bring their entire output to the market and bid in price. The lowest bidder takes all the demand of the market and the loser does not produce at all.
    The result of this theoretical model for oligopolies is similar to the outcome of competitive market models because a Producer which offers different than its marginal cost may lose. If its bid is higher than the competitors, then it does not produce at all. If its bid is lower than its marginal cost and lower than its competitor bid, it will not recover the generation cost.

At first glance, Bertrand Competition seems to be adequate to represent electricity markets games. However Borenstein and Bushnell (1999) noticed that this Bertrand Competition is inappropriate because it assumes that each company can expand output sufficiently to serve the entire market, which is unlikely to be the case in electricity markets. Kreps and Scheinkman (1983) taking Edgeworth's idea as a starting point[7], showed than in a two step game the result obtained is equal to the Cournot equilibrium.

4.2 Market Power in Electricity Markets

This section provides the definition of market power related to electricity markets.

At first some countries neglected the implementation of market monitoring systems, and until the late 90's the issue of market power was limited to mergers and acquisitions. The idea was to allow the market to auto-regulate the industry. The market power issue gained importance since it erodes the benefits of the deregulation of the electricity markets. However detecting and proving the existence of market power is a difficult task and there is no single method to determine market power but only a set of indicators, David and Wen (2000) claimed that:

> If a generator can successfully increase its profits by strategic bidding or by any other means other than lowering its costs, it is said to have market power.

According to Twomey (2005) the primary methods for exercising market power are: (1) physical or quantity withholding, (2) financial or economic withholding and, (3) transmission related strategies. Physical withholding implies deliberately reducing the output that is offered to the market even thought the output can be sold in the market. Financial withholding implies that

[6]Doupoly is a situation in which two Producers control the market.

[7]Edgeworth's initially intended to include constraints on production capacity in the Bertrand or competition on price model. He aimed to show that the oligopoly problem was essentially indeterminate, contradicting the approach adopted by Bertrand, who had in turn criticized Cournot's competition model.

bidding prices are higher than the competitive bid for the block of electricity output. The transmission strategies involve creating or worsening transmission congestion in order to raise prices in a given zone or node. Method (3) can only be exercised by the Transmission System Operator. Methods (1) and (2) can be used by producers which would generate a leftwards shift in the supply curve (output withdrawn) or an upwards shift (raise of bid price). These strategies have an effect on the merit order, thus distorting the price signal Twomey (2005).

The definition used in this thesis regards market power as the act by which Producers strategically bid prices different than their marginal cost. This definition does not incorporate the notion of physical withholding because it is assumed that Producers bid all their output.

4.3 How Agents Learn?

This section given a brief overview of some learning behaviours which could represent the strategic bidding in electricity markets.

In agent-based models, agents undertake a behaviour based on the rules and states. In the case of electricity markets, Producers should adapt their bid by means of a learning algorithms. A learning algorithm considers adaptive behaviour of goal-oriented players who may not be rational (Erev and Roth, 1998). The basis of the learning considers psychology of learning, usually intuitive formulation of the learning process. These underlying considerations define different learning algorithms used to reflect strategic bidding. For example reinforcement learning, Q-learning and Probe and Adjust to name a few (for a further inside of different learning algorithms, consult Weidlich and Veit (2008)).

If agents apply reinforcement learning, they adjust their bidding strategies according to their last round's success; they either lower, raise, or repeat their last bid depending whether profit targets have been met in the last round or not (Kaelbling et al., 1996). With Q-learning, an expected reward is introduced into the algorithm (Kaelbling et al., 1996). Probe and Adjust algorithm is a local heuristic method Kimbrough and Murphy (2009), in other words agents learn through trial-and-error interactions with a dynamic environment.

In the case of reinforcement learning and Q-learning, the all results from the past keep influencing[8] the future decision; meaning that agents have an unlimited memory. Moreover, in Q-learning the agent should make estimates of the possible outcome in future moves. However, the agent which undertakes the Probe and Adjust algorithm makes small increments after a learning period by experimenting. From these learning algorithms, Probe and Adjust is selected given that Producer might have limited rationality to make good estimates of the future, and will not remember all the information from the past.

4.4 Learning procedure, Probe and Adjust Algorithm

This section describes the algorithm selected to represent strategic bidding in electricity markets.

The algorithm introduced by Kimbrough and Murphy (2009) aims to capture the learing process by which an agent learns through experimentation, a trial-and-error methodology (see Section 6.2 for detail of the algorithm). Basically the agent makes small increments going up or down on their bids based on previous results every certain period of time. This period of time represent the time an agent need to make a decision. Kimbrough and Murphy (2009) indicated a learning time (EPochlength) value of 50, but he did not make an analysis of the implication of this value. Moreover, he did not indicate the values of the incremental modification of the

[8] This influence decrease with every step the agent takes, but it does not disapear.

memory bid (Delta) and later this values proved to have a high impact on the model (see Section 7.3). Another aspect is the effect of the algorithm when the average profit up is equal to average profit down since with a unique action price mechanisms (generally used in electricity market) some producers might have the same profit whether they bid up or down (see Section 2.6).

- **Producer Learning Process** The algorithm developed by Kimbrough and Murphy (2009) is applied to the Producers in the system *European Wholesale Electricity Market*. Producers learn by a process of trial-and-error depicted in Figure 4.1. At the beginning of the process, each producer has a memory value of the bid $MBid_i^1$ with which he will make some bidding experiments $EBid_i^1$. The value of $EBid_i^1$ is equal to $MBid_i^1$ plus a certain percentage (range). If the value of $EBid_i^1$ is higher that $MBid_i^1$, then the profits obtained will be stored in a memory set called Profit up. Conversally, if the value of $EBid_i^1$ is lower that $MBid_i^1$, then the profits obtained will be stored in a memory set called Profit down. The memory size is expressend by EPochlength, and has a value equal to n. This means that the Producer makes experiment n-times after making a decision based on the results obtained. At the end of the n-trial, the Producer will assess the average value of the Profit up and Profit down. If the Average Profit up is higher that the Average Profit down, then the Producer will realize that from his past n-experiments, in average was better to bid higher than $MBid_i^1$, therefore the next value of its memory will be $MBid_i^2 = MBid_i^1(1 + Delta)$ where Delta is a percentage of increase[9]. In the event that the Average Profit up is lower that the Average Profit down, the same logic applies but in this case the next value would be $MBid_i^2 = MBid_i^1(1 - Delta)$. Before starting a new set of experiment, the values of the Profit up and Profit down are eliminated so the agent looses that information forever. This means that the agent only makes decisions based on a limited amount of past information and disregards all the other past outcomes. With the new value of memory $MBid_i^2$ the Producer will make another experiment n-times.
  Although Kimbrough and Murphy (2009) indicate that if Average Profit up is equal to the Average Profit down the next memory value should go up (see Algorithm 6.1), this research experimentated with 4 different options, namely: increase its memory value by Delta, decrease its memory value by Delta, stay in the same point (Delta=0) or try randomly to go up or down. These experiments were done on the basis that the event where Average Profit up is equal to the Average Profit down happens quite frequently and could be a key aspect of the model. This detailed has a significant effect in the model output as Section 7.3 explains.

[9]The percentage of increase (Delta) is lower than the percentage that the agents experiment (range). This can be interpreted as: although the experiments indicated the direction to move (up or down), the Producer is causious and make small increment.

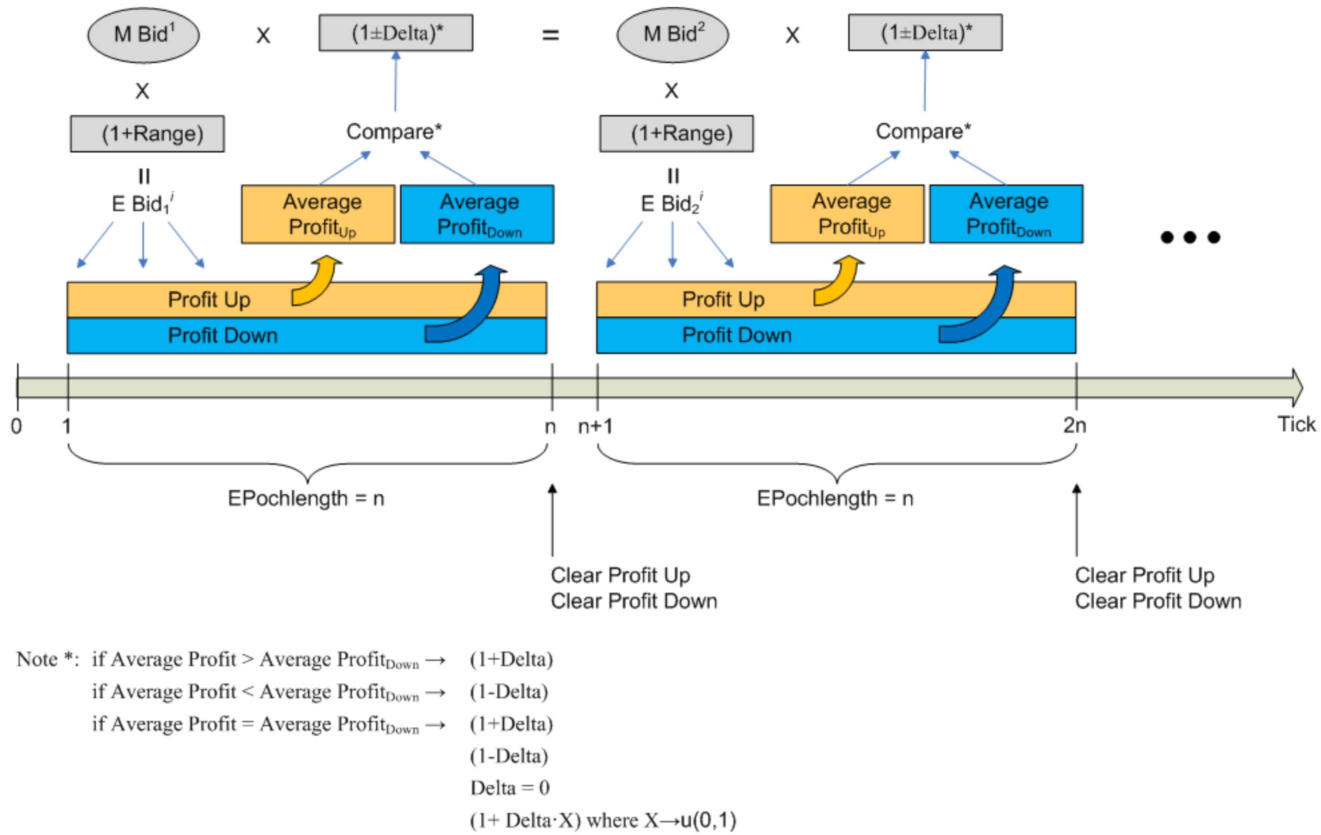


Figure 4.1: Producer learing process - Prove and Ajust algorithm.

4.5 Chapter Conclusion

The current electricity markets have characteristics which differ from perfect competitive markets; this implies that a Producer can increase its profit through strategic bidding, i.e. by exercising market power. Transmission constraints can isolate markets and enhance Producers market power. The definition used in this thesis regards market power as the act by which Producers strategically bid prices different than their marginal cost. This definition does not incorporate the notion of physical withholding because it is assumed that Producers bid all their output.

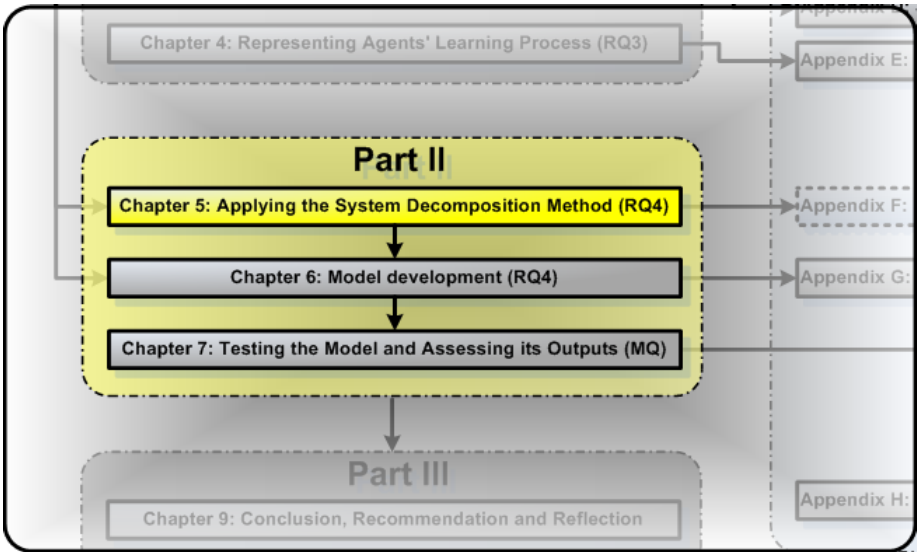
Agents learn by adapting their bid position which by means of a learning algorithm, the agents maximize their own profit when they bid into the market. A learning algorithm considers adaptive behaviour of goal-oriented players who may not be rational. Examples of learning algorithms used in agent based are: reinforcement learning, Q-learning and Probe and Adjust. Agent using reinforcement learning either lowers, raises, or repeats their last bid depending whether profit targets have been met in the last round or not. While using the Q-learning, an expected reward is introduced into the algorithm. When the Probe and Adjust algorithm is used, the agents learn through trial-and-error. From these learning algorithms, Probe and Adjust is selected given that Producer might have limited rationality to make good estimates of the future, and will not remember all the information from the past.

Part II

Model Development: Abstracting Actors into Agents

Chapter 5

Applying the System Decomposition Method



Provided that the system is regarded as a Complex Adaptive System, the system decomposition method is a suitable methodology to capture the internal structure of the system as Nikolic et al. (2009) concluded in his Phd. Thus this chapter undertakes system decomposition and by so, it starts answering RQ4. Section 5.1 reveals the economical and physical system characteristics which his will define the system in Section 5.2. In Section 5.3 the backbone of the system is presented, i.e. the agents interactions, states and rules. Section 5.4 summarizes the boundaries of the system.

5.1 System Description

This Section starts with the system description of the electricity wholesale market abstracting it into two underlying layers. Afterwards these layers which defined the level of agents' interaction are described.

The liberalization of the electricity sector divided the once vertically integrated electricity undertaking into different segments of the value chain, namely generation, transmission network, distribution network, and retailing. The electricity produced is sold in a market where producers offer the amount of electricity they are willing to generate at a given price whereas consumers bid the quantity of electricity they want to consume at a given price. These contracts can be made in two market places, in a power exchange or in a bilateral market; both part of the *Wholesale Market*. Although the electricity market typically consists of a *Power Exchange* and *Bilateral Market*, in this thesis, the electricity can only be traded though a centralized power exchange (*Pool*), in other words Producers cannot sell electricity directly to Consumers. The reason to assume a pool-like market is because of the electricity prices in bilateral agreements are fixed for a medium to long period of time and the focus of this thesis is the short-term. Moreover, prices in spot markets signal prices in bilateral contracts as a reference (Vries et al., 2009) and prices of bilateral contracts are kept private.

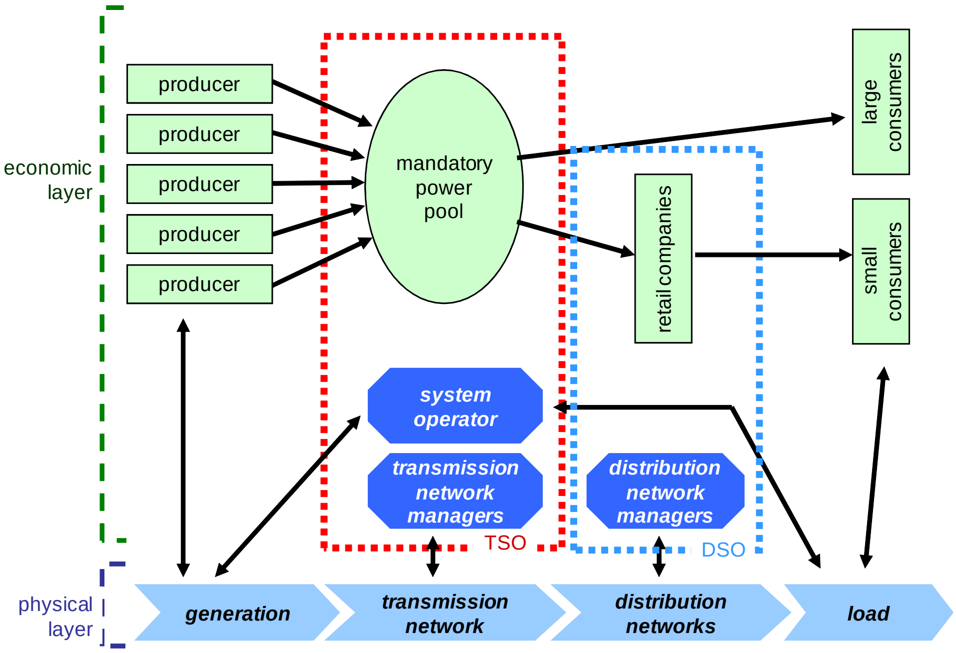


Figure 5.1: The electricity sectors layers (Vries et al. (2009))

On the basis of only considering spot markets which trade electricity for the next day for the settlement period[1] through a unique Pool market, Figure 5.1 depicts the system components. The central idea is that the Pool operator receives prices and quantities submitted by Producers and selects the most efficient sources of supply to demand of Consumers. In this thesis, the Pool operator is the Transmission System Operator who is also in charge of the management of

[1]Tipically the settlement period is 1 or $\frac{1}{2}$ hours.

the network, see Section 5.4. The winning bidders are paid the same price regardless of their individual bids[2] (in the market clearing process) and consumers pay this price. Consumers can be either retailing undertaking (which represent small consumers by aggregating their demand) or large consumers.

Within the electricity system, there are two coexisting layer, the economic and physical layer. While the economic layer deals with the transaction done to supply electricity, the physical layer deals with the flow of electricity from the generation side to the end consumer. The transactions are contracts between Producers and Consumers (retailers) traded in the mandatory power pool. These trades are managed by the TSO, and can only take place in the wholesale market[3].

The transmission network wheels the electricity at high voltage to reduce the loss, and connects the power plants with the distribution network. After reducing the voltage though transforms, the distribution network connects small and some large Consumers at lower voltage. In some cases small power plants are directly connected to the distribution network and some large Consumers are connected to the transmission network.

Based on the objective of this thesis, the physical and economic layers are respectively abstracted into techno-sphere and socio-sphere, see Figure 5.2. A three node configuration is adopted because it is the minimum configuration requirement to create the scenario with congestion and so understand how market participants bid by means of a simulation model.

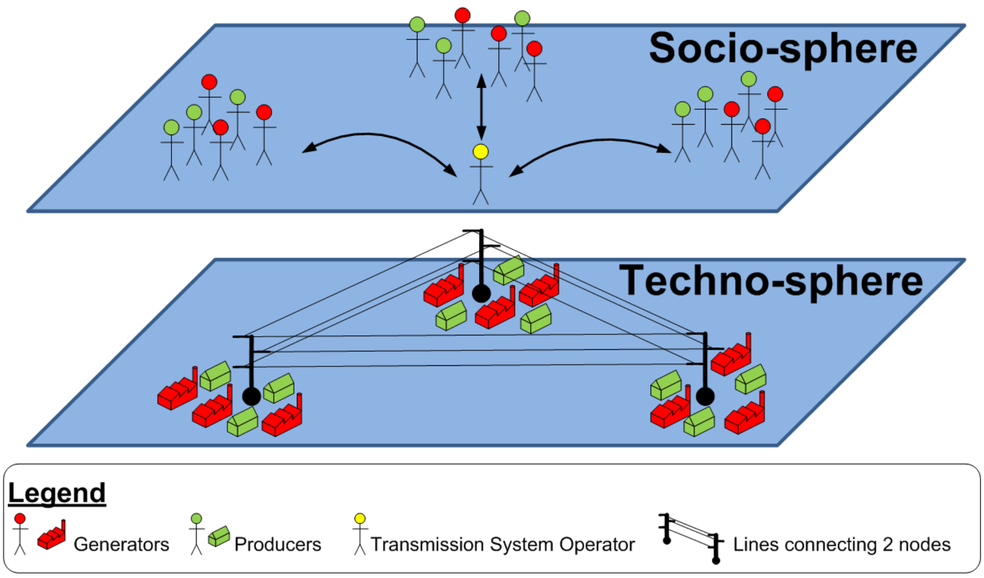


Figure 5.2: Techno- and Socio-sphere

The techno-sphere takes into account limitation of electricity production and transmission, whereas the socio-sphere supports agent's interaction. Both of these interconnected layers aim to reveal the complexity of the system and will define the playing ground so the interaction of agents will give as result the emergent system.

[2]This means that the auction is non-discriminatory and bidders which are in the merit order, receive a uniform price.

[3]Trades are only allowed at wholesale level if the degree of competition only goes until the wholesale. However, if there is competition at the retailing level, then trades are allowed at this level. For this thesis, it is assumed competition at the wholesale level.

Techno-sphere

This layer makes reference to the technology and physical constraints, and given the short-term focus of this thesis, these characteristics do not change through the simulation. These characteristics are: the technology used, capacity of the power plant, the cost involved to produce electricity and the line capacity between nodes in the electricity network. The technology used by each producer directly affects the cost of production of electricity, for example coal-fired plants have lower fixed cost in comparison with nuclear but higher variable cost. Fixed cost independent of the electricity production whereas variable cost is affected by the generation of electricity. The capacity of the lines is the maximum allowed power flow of electricity that the line admits to work within security limits. Although there are methods to increase the capacity of the lines, these methods can only be used in the long term and thus will not be considered. The techno-sphere restricts the decisions taken in the socio-sphere since agents cannot modify the characteristics of the techno-sphere.

In this thesis, it was assumed a 3-node network market in which Producers are distributed in node 1 and 2 whereas the aggregated Consumers are placed in node 3 (see Figure 5.3). For identification purposes, power plants are assigned[4] with a capital P (making reference to power plants[5]) with two number, the first refers to the Producer identification and the second is the power plants identification. It is assumed that there are 3 Producers in the network (Producer 1, 2 and 3). While Producer 1 and Producer 2 have 2 generation plants each one, Producer 3 has one power plant. For example P_{23} refers to Producer 2 and powers plant 3. Note that power plants are identified from 1 to 5. Each one of the Producer might generate electricity, so they will produce a flow in t all the lines of the network.

The flows obey Kirchoff rules, and basically electricity flows from the generation side (node 1 and 2) towards node 3. However the amount of flow is different according to the position of the electricity production with respect the consumption. The difference is a function of the resistance of the connection lines between input and output of electricity. The more resistance, the less electricity will flow through a cable[6].

In the configuration assumed in this thesis (see Figure 5.3), the resistence of all lines are the same, and the amount of flow from the generation plants situated in the node 1 (P_{14} and P_{35}) though the line 0 is $\frac{2}{3}$ of the total electricity production from node 1, whereas for the line 1 and 2 is $\frac{1}{3}$ of the total electricity production from node 1. Conversally for the case of power plants placed in the node 2 (P_{11}, P_{22} and P_{23}), the flow through line 2 is $\frac{2}{3}$ of the total electricity production from node 2 and through line 1 and 0 is $\frac{1}{3}$ of the total electricity production from node 2. Given that electricity flow from production side towards consumption side, the flows have directions. Based on the superposition principle, flows can be added, so in the case of line 1 it has $\frac{1}{3}({P^G}_{11} + {P^G}_{22} + {P^G}_{23})$ which is the contribution of power plants in node 2, minus $\frac{1}{3}({P^G}_{14} + {P^G}_{35})$ which is the contribution of power plants in node 1. It can be seen that, line 1 is less likely to be congested given that flow go in different direction and line 2 is more likely to be congested[7] since it has higher contribution from power plants in node 2 than from plants in node 1.

[4]In the model introduced into Java language, the Producers where assigned a 2 at the beginning of the index for identification purposes. So what Figure 5.3 presents as P_{23} in the model is P_{223}.

[5]It has to be noted that power plant in different from Producers, since a Producer might have several power plants in his portfolio.

[6]The electricity flows through all the connection cables, this means that if a two points are connected by multiple lines, the flow will be inversally proportional to the relative resistance of the lines.

[7]The probability of being congested is in the assumption that power plants have more or less the same price and would be in the merit order (will produce electricity).

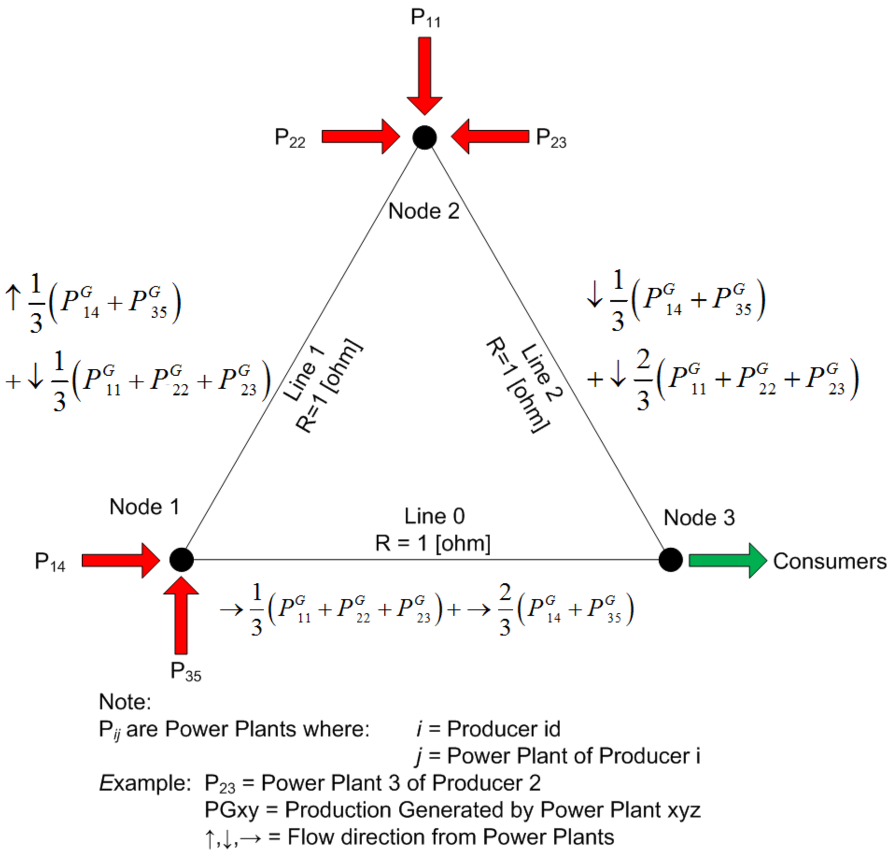


Figure 5.3: Technosphere in detail

Socio-sphere

This layer represents the multi-agent environment which the agents take decisions and interact amongst them. The decisions and outcomes of the interactions are restricted by the conditions in the techno-sphere. Basically the interaction is: (1) between the *Transmission System Operator* and the *Producers* and (2) between the *Transmission System Operator* and the *Consumers* (see Section 6.1 and Figure G.1 for further detail).

The result from the interaction between the market players is decided on economical basis, meaning that the most economical power plants (owned by Producers) should supply to consumers who value electricity the most.

As explained before, the are 3 Producers with a total amount of 5 generation plants in the Technosphere layer. Each Producer decides its bid position composed of a price and its maximum output. The bids position are submitted to the TSO[8]. Since Consumers are assumed to be static in this thesis, their demand remains constant to any market outcome.

Figure 5.4 exemplifies the clearing process that the TSO undertakes.

[8] In the case of a centralized maket, and in this thesis, the TSO undertakes economical and technical functions.

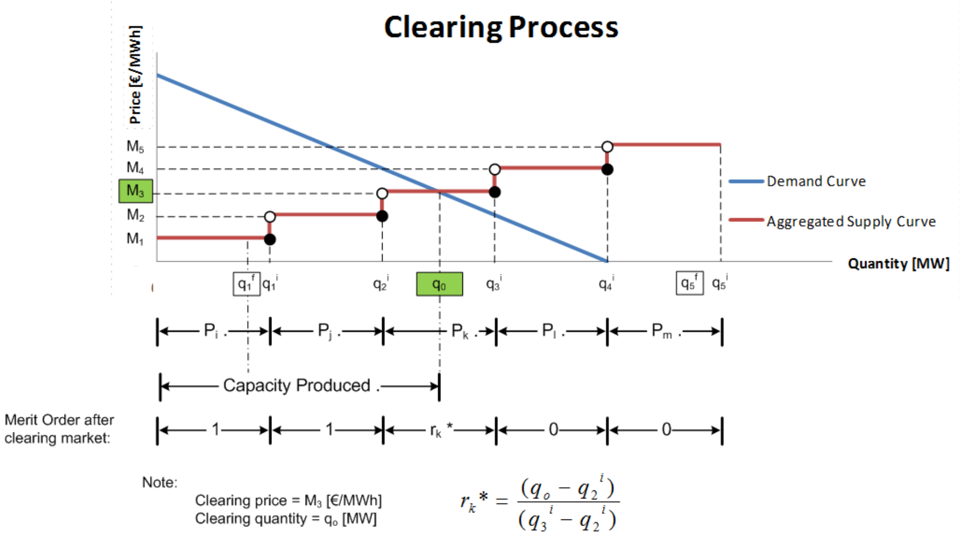


Figure 5.4: Sociosphere: a electricity auction process.

The TSO builds the aggregaded supply curves with the Producers bids and matches it with the Customers' demand curve. This produces the clearing price M_3 , the cleared quantity q_0 and the merit order[9]. The merit order indicates that P_i, P_j produce at full capacity and P_k produced at a r^*_k ratio; and that the generation plants P_l, P_m do not produce. The power plants which produce either at fully or partial capacity receive the same price for the electricity M_3. Note that the demand curve intersects the supply curve between two acumulated quantities, however the clearing price might be as well between two offered prices (see Appendix F for an example of these cases).

5.2 System Diagram

This Section delineates the problem based on the system description explained in the previous Section.

The system diagram reveals the boundary and the components of the system, the external factors involved, the objectives that the problem owner is interested to meet and the plausible policies which change the systems behaviour. With reference to the *European Wholesale Electricity Market*, there are three agents who interact amongst them, see Figure 5.5.

[9]For this thesis, it was assumed that the merit order is a value between 0 and 1 for each power plants. 1 indicates that the power plant produces at full capacity, 0 means that the power plant does not produce, and a value betwenn 0 and 1 is the ratio of real production over the maximun output of the power plant.

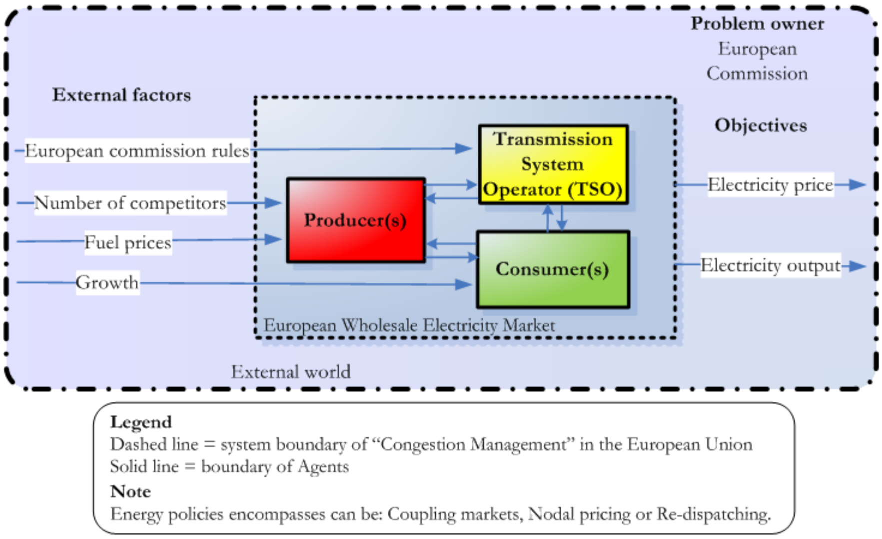


Figure 5.5: System diagram.

The external factors are variable which are outside of the systems scope given the short-term focus and/or the problem owner cannot influence them. These factors account for internal-market constraints and socio-economic constraints.

The internal-market constraints are the conditions of the electricity market industry. These constraints are *European Commission rules* and *number of competitors*. Although the former constraint is obviously steered by the problem owner, given the short-term focus, this rules are assumed to be constant, i.e. the congestion mechanism are fixed throughout the modelling run. In the case of the factor *number of competitors*, the amount of market producers will be fixed for every run, this means that they cannot go outside (in the case of bankruptcy) or increase (new entrants).

The socio-economic constraints are condition determined or assumed to be caused by other actors outside the influence of the problem owner within the time horizon. These constraints are *fuel prices* and *growth*. The fuel prices are determined in global markets and cannot be influenced by the European Commission. Although the factor *growth* accounts for the increase of consumers, and thus increase in electricity demand, the large inelasticity in the short-term result that producers do not react to the change of price, in other words, the consumers will demand almost the same quantity of electricity even though there is a change in the electricity price. For this thesis, the *fuel prices* and *growth* assumed to be fixed given the short-term focus.

5.3 Agents Inventory

This Section reveals the principal characteristics of the agents at network and agent level. This means that interactions of the agents, i.e. the typical activities; and the characteristics of each agent are presented. This explanation focus on the main aspect that the thesis is interested in.

The agent formalisation is a conceptual bridge that eases the communication tool amongst different knowledge domains (Beers et al., 2007). Domain experts may have different vocabulary and perceptions of how the system works, for example it is different how economics and electric engineering assess the congestion issue. While economics sees an allocation problem of the scarce resource (line capacity) amongst the party who most values it, engineering sees a limitation of installed capacity. The variety of views can produce conceptual ambiguities to capture the essence of the problem and the system itself.

The agent formalisation provides common relevant information which can be easily shared amongst domain experts. The formalization process basically aims to capture the aspect of interest of the system. In this case the activities performed by the agents will define their states and rules.

Agents Activities

Relation between agent and environment, and relations amongst agents are abstracted into this level. Taking the four-level model of Williamson (1998), the dynamic between the third level (governance structures) and the fourth level (marginal condition right) can be represented into agent-based realm. The market players (abstracted as agents) interact among them and learn within rules imposed by the government (congestion mechanism). This means that the scarce capacity allocation (fourth level) is the result of the agent interaction given a set of rules (third level), see Figure 5.6. Groenewegen and Künneke (2005) argued that there is a logic between the levels of institutionalization; a feedback of information between the levels. Nevertheless the research will focus is on the short-term; therefore it will not take into account these feedbacks since they take years.

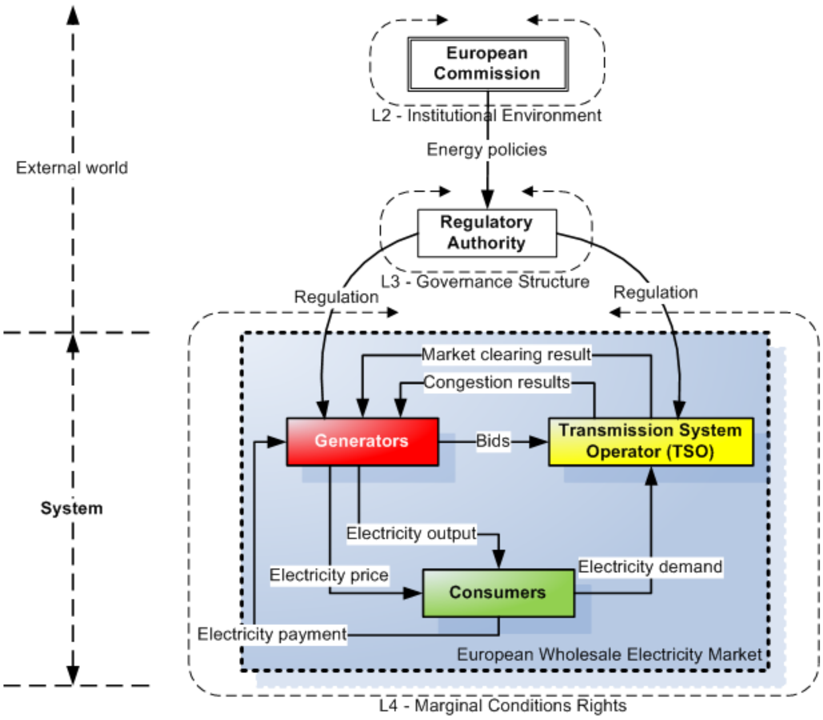


Figure 5.6: Network diagram

Agents Description

On the basis of the agent activities, the particular characteristics each agent entitles define the state and rules. These characteristics define the output of each agent, in other words the final decision or procedure an agent performs. On the basis of the agents description, the agent will be represented by state and rules algorithms, see Section 6.1.

Producers Are profit seekers and might strategically bid, given the short-term focus, to gain extra profit. The *strategic bid* corresponds withhold price (in the sense to bid different than marginal cost). The final bid is the result of the internal algorithm of the strategy which takes into account the electricity price and the profit obtained (see Section 4.4 for further detail). Information such as the merit order and the market price, are published by the Transmission System Operator. With this information, each Producer calculates its profit. The profit is the final result of selling electricity at a uniform market[10] price less the expenses to produce electricity which depends on the technology the Producer selected. The technology each producer opted to form its asset determines the capacity and marginal cost. Thus the Producers' states can be summarized into: *Technology*, *Information, Economics* and *Memory* (see Section 6.1 for further explanation).

Transmission System Operator (TSO) Has to manage the market and manage the network (like in the case of centralized markets). Thus, the TSO is in charge of clearing the market in which Producers and Consumers bid. Moreover, and to clear congestion if at least one flow overpasses the maximum line capacity. In order to clear the market, the TSO collects the bid positions of both, Producers and Consumers. This means that the Transmission System Operator's states are: *Information* and *Market procedure.* After the curves are matched, the cleared price and quantity are publicly available to all market players. If there is congestion, then the TSO must arrange the electricity generation by means of re-dispatching (see Section 2.6 for further detail on re-dispatching). These two procedures define the rules: *Market Clearing* and *Congestion Clearing* (see Section 6.1 for further explanation).

Consumers Represent an aggregate demand for electricity of all electricity customers (small and large consumers). The consumers are passive entities which do not adapt or self-organize. This means that the only interaction with the Transmission System Operator is the submission of its electricity demand but there is no interaction with the Producers, i.e. no bilateral market. Regardless of the electricity price, consumers will demand electricity and will pay the price found in the clearing process. Therefore, this agent has only states and no rules. The consumers' states are: *Needs* and *Economics* (see Section 6.1 for further explanation).

5.4 Assumptions

In this Section, after the system has been described, the main assumptions are summarized.

Every model is an abstraction of a particular aspect of reality. Since it is impossible to capture all the details of reality, the assumption done influence the model's output. This assumptions are classified into system, agent and network assumptions; which correspond to the system levels of an agent-based approach (see Section 6.1).

Emergent System

The following assumptions regard to the attributes of the emergent system which define the techno-sphere layer (see Section 5.1).

[10]The unique auction price is used to clear the electricity market.

Short-term focus: This is the one of the main assumptions of the model since this affects the interest and decisions of agents who will maximize their profit without considering the long-term consequences.

Pool-based market This type of market arrangement allows the use of local marginal pricing (or nodal price), zonal pricing and re-dispatching Krause (2007).

3-node configuration: Each node supports either a Producer or a Consumer. For this thesis, a 3-node system in which 2 nodes attain producer and in 1 node Consumers are placed is selected because the objective is the determination of strategic bidding on the basis of a simulation model and to get insight of the process. Therefore, a simple configuration can give revealing and basic results which could be tested in a more complex network setting.

No specific geographical characteristics Although the scope is the European Union, the system definition regards the possible rules which can be adopted within the EU and do not regard the particular physical factors[11], economical factors[12] or institutional factors[13] of the European Union (factors used from Vries et al. (2009))

No market restructuring The performance of the rules imposed in the market triggers the government's response to adapt mechanism and laws. However the feedback from the market outcome towards the decision makers takes long time. Since the short-term focus of this thesis, the congestion management mechanisms are invariable through the model run.

No network losses The conduction of electricity though a wire causes energy losses in the form of heat. Producers must generate more electricity than the demanded knowing that some of this energy will be lost. However, for the scope of this thesis, losses will not induce any kind of strategic behaviour since with or without congestion losses are present.

Interconnection resistance: The resistance of the lines determines the actual electricity flows in each line. For calculation issues and given that the focus is the strategic behaviour rather than a calculation activity, the resistance are taken as equal.

Network of Agents

3 agents interaction Although the issues has been defined as a multi-actor problems, the most interesting actors with respect the objective of this thesis and its scope are the *Producers*, the *Transmission System Operator (TSO)* and the *Consumers*. This implies that the agent in charge of matching supply and demand while managing the transmission line is the *TSO*, in other words the *TSO* is the market operator and the system operator.

No bilateral market In case of bilateral market, transaction between producers and customers are possible, in other words they interact directly. On the contrary, a mandatory pool arrangement only allows transactions through the centralized pool, and so it producers and consumers separately interact with the market operator.

[11]Physical factor are: natural endowment with energy sources; physical size of the market; and geographical distribution of demand in relation to network capacity.

[12]Economical factor are: level of economic development and growth; growth rate of demand; and financial options.

[13]Institutional factors are: ideology; institutional stability and rule of law; degree of institutional centralization and homogeneity; and influence of stakeholders.

Agents

The assumptions taken to this level shape the decisions taken by the agents at the socio-sphere layer (see Section 5.1).

- **States**

  No technology innovation Although it is reasonable to expect that increased competition among generators will lead suppliers to increase efforts to improve the performance of their units, given the short-term focus the technology and efficiency of the power plants are fixed.

  No stranded costs In case of liberalized market; the price is expected to fall. If prices fall below regulated prices, utilities may not be able to recover all the costs they have incurred in the past to serve their customers. This difference is known as stranded cost, and could give an extra incentive to agents to strategically bid to recover the difference[14].

  Consumption demand constant The demand curve of the aggregated Consumers is set as fixed, this implies that consumers do not react or adjust their demand and so probably give room for strategic behaviour from the Producers side since they can bid any cost and will no reaction from the consumption side.

  Same production costs The variable and fixed cost of each generation plant is assumed to be the same for all Producers.

  Fixed production costs The cost of electricity production are considered to be constant throught time given the short-term focus.

- **Rules**

  Logic decisions The decisions are based on a software code which based on the inputs and the states of the agent, will give a result. The result is regarded as logic in the sense that they follow an algorithm.

5.5 Chapter Conclusion

On the basis of the *system decomposition* methodology, 3 different types of agents are identified to define the main interactions which take place in electricity markets in the event of congestion. The agents are: *Producers*, the *Transmission System Operator (TSO)* and the *Consumers. Producers* are profit seekers and might strategically bid to gain extra profit. The *TSO* is in charge to manage the market and the transmission system. *Consumers* represent an aggregate demand for electricity of all consumers (small and large consumers). These agents have different technical and economical activities.

The technical and economical common activities in the electricity market are abstracted into two techno-sphere and socio-sphere layer. The techno-sphere captures the physical conditions which are fixed given the short-term focus of this thesis. The socio-sphere contains the interaction of the 3 agents, these interaction are limited by the conditions on the techno-sphere. The agent has different states and rules which affect the decisions taken by the agents. While states are

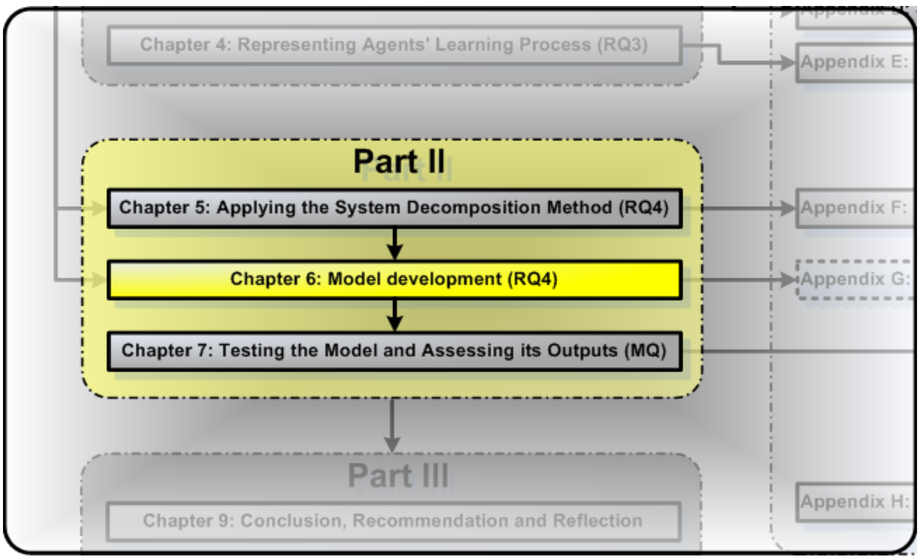
[14] The differential costs (including capital recovery on previous investments) will become "stranded." For example, for a particular plant, if the price of electricity falls to 3.5 cents per kilowatt-hour and the regulated cost of service from the plant is 4.0 cents per kilowatt-hour (including regulated capital investment recovery), the 0.5-cent difference will be stranded.

attributes of the agent, rules are the decision algorithms which depend on the state and agent's inputs. Some assumptions were made so as to delimit the boundary at the emergent system, agent and network level.

At the emergent level the short-term focus will fix technological and markets structure changes. The network constraints define the 3 agents interacting in a 3 node electricity grid where bilateral contracts are not allowed. At the agent level, the techno-sphere and the market outcomes define agents' states. The agents' rules are assumed to be logical in the sense that they respect and follow a software code which may represent a rational behaviour.

Chapter 6

Model Development



In this Chapter the internal structure of the system captured in the previous Chapter, will be translated into a formal language. Section 6.1 presents the Complex Adaptive System framework applied to the system. Section 6.2 presents the Producer's learning algorithm developed by (Kimbrough and Murphy, 2009). The physical network configuration is presented in Section 6.3. This consideration will lead to the overall system activities explained in Section 6.4. Section 6.5 describes the simulation strategy and the experiments performed. Finally Section 6.6 mentions the output values which were analyzed.

6.1 Systems Levels

This Section takes the findings of Chapter 5, put them into the system level and expressing them into machine-readable language. First the emergent system presents the main actors and their coordination amongst them. Second the network level detail the relation between agents. Third and finally, the agents' states and rules are expressed in mathematical terms which were introduced into the model in Java code.

As seen in Section 3.1, the *European Wholesale Electricity Market* system is a Complex Adaptive System, and needs an especial framework to be described and understood. Nikolic et al. (2009) proposes a framework to abstract the system characteristics which implement a holistic view and reduction view (see Figure 6.1 and consult Nikolic et al. (2009) if further insight is needed). Both of these views are need to explain a Complex Adaptive System.

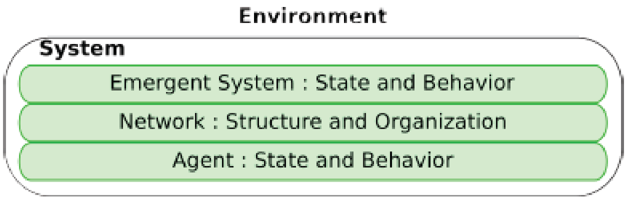


Figure 6.1: System levels (Nikolic et al., 2009).

Emergent System Level Presents the emergent system properties caused by interaction of agents at network level. The system level makes reference to the macro level of the system, in other words the electricity market.

Network Level Contains the structure of interactions amongst agents. At this level the agent's relation form the structure of the network and describes this interaction in terms of nodes and edges. The network level corresponds to the meso level which deals with the market clearing and congestion clearing process.

Agent Level Correspond to the smallest detail of the system represented by agents. The level makes reference to the micro level where agents are described in terms of states (agents' attributes) and rules (decision logic which depends on agents' states and inputs).

Emergent System Level

The overall agents interactions result in the emergent system, this means that the market is the result of the interaction between market participants. The market participants[1] is composed of suppliers (Producers) and demanders (Consumers) and a body in charge on managing the flows and matching supply and demand (Transmission System Operator). The emergent system is illustrated in Figure 6.2 which reveal the most important agents and their interactions in accordance with the objective of this thesis.

[1]See Appendix G of the details of each market participant in terms of attributes and methods in a the class diagram.

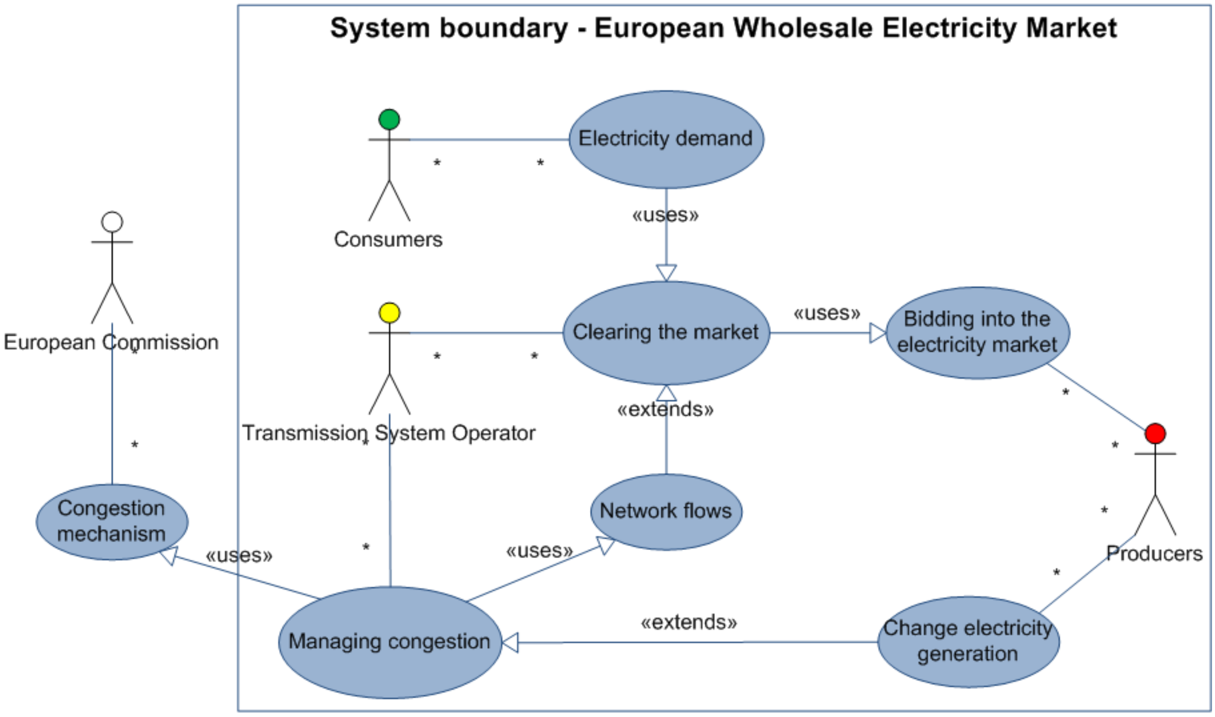


Figure 6.2: Emergent system.

Within the system boundary, the *Transmission System Operator*, the *Producers* and the *Consumers* interact amongst them. The *European Commission* settles the congestion mechanism which will be used to solve the system but its interaction is out of the system because in the short-term (focus of this thesis) the feedback of information is neglectable (see following Section for further explanation).

The market is solved or cleared by the *Transmission System Operator*, who with the electricity demand, the bids position applies the market clearing algorithm and if there is congestion, applies the congestion algorithm. The *Consumers* operationalized their need of energy to sustain their quality of live in terms of electricity demand. The *Producers* will reflect their willingness to produce electricity in terms of a bid position which is basically the amount of electricity they would like to produce at a certain price. The price that Producers bid are regarded as their cost of production by the TSO, but this does not imply that they are their real production cost, in other words, Producers might bid higher than their production cost with the aim to gain extra profit.

In the event of congestion, the TSO uses re-dispatching which in principle re-schedules the electricity generation. This result in a shift of electricity generation by which Producers receive payments from the TSO for not producing electricity which will put in risk the network or are reimbursed for being re-dispatched even though they were not inside the merit order (see Section 2.6 for detail on re-dispatching mechanism).

Network level

The periodic process that *Consumers*, *Producers* and the *Transmission System Operator* undertake to supply electricity is represented in Figure 6.3 and in detail in Appendix G.

The ticks are discrete time representation of the start and end of interaction. The first tick ($t = 0$) will assemble the system and no agents' activities are undertaken, whereas from the tick $t = 1$ onwards, the agents will interact between them undertaking different activities. The interaction will stop when the stopping rule is met, see Section 6.5.

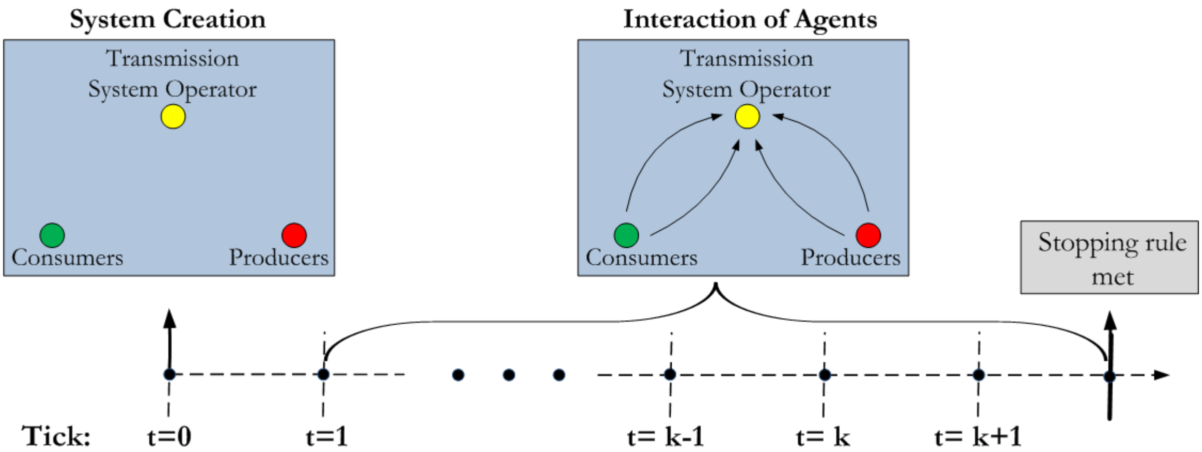


Figure 6.3: Run of the model.

Agent Level

In liberalized electricity markets there are many functional components[2] or agents. An agent consist of inputs and outputs which represent links with other agents in the system and information with the external world. The agents have the property of adaptiveness and self-organization[3] based on their particular states and rules. States are specific collection of relevant parameters that define an agent.

[2]A functional components are defined by the system, and outside of it they have no meaning. In case that a functional component is removed from the sytem, then the system will lose its original identity as a whole system.

[3]Self-organization and adaptiveness are emergent behaviours which results in a different output. While the former is achieved by internal agent interaction, the latter is caused by a change in the environment that triggers a modification at the agent level.

- **Transmission System Operator**

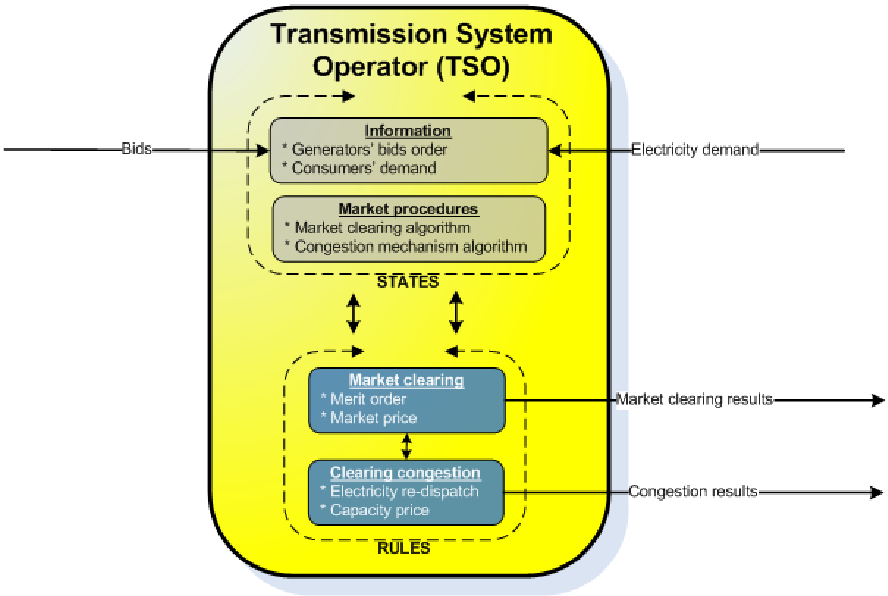


Figure 6.4: Transmission System Operator's states and rules

- **States:**

  - Clearing price: price at which demand and supply curves intersect. $clearedPrice_i \in (0, 200)$ this limits[4] the price between 0 [€/MWh] and 200 [€/MWh].

  - Clearing quantity: quantity at which demand and supply curves intersect. $clearedQuantity_i \in (0, 250)$ this limits[5] is quantity 0 [MW] and 250 [€/MWh].

  - Merit order: is the ratio of electricity to be produced by all generation plants. The ratio measures the amount of electricity to be produced based on the maximum capacity of the generation plant.
    $\{r_1, r_2, r_3, r_4, r_5\}$where $r_i \in (0, 1)$

- **Rules:**

  - The market clearing process matches supply and demand curve of electricity (see Section 5.1 for further detail)

  - The congestion clearing procedure assumed is the re-dispatching mechanism (see Section 2.6 for further detail)

[4]The upper cap whas established to avoid high clearing prices.
[5]The upper cap is the total amount of capacity off all genertion plant assuming a capacity equal to 50 [MW] per 5 generators.

- **Producers**

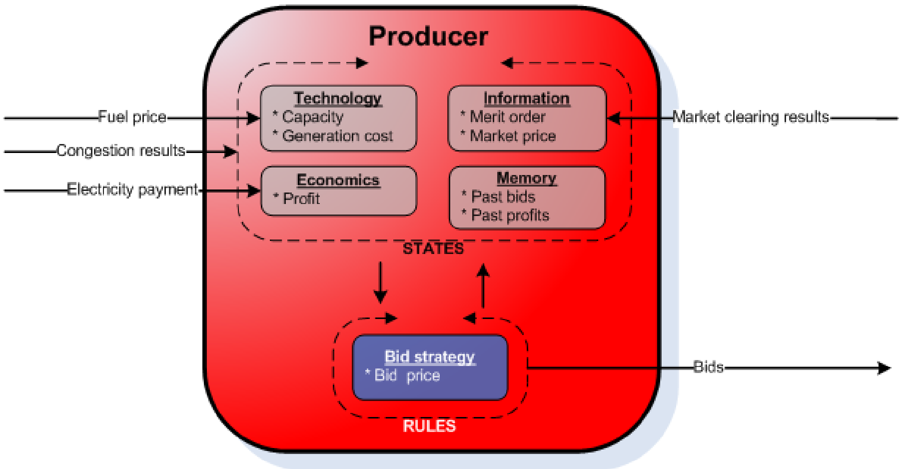


Figure 6.5: Producer's states and rules

- **States:** The producer has a sequence of memory bids, profit up and profit down information (see Section 4.4 for further detail).
  - Memory Bid: is a sequence of information of the bid which starts with an initial value at tick $i = 1$ until the end of the model run $i = m$
    $\{MBid_i\}_{i=1}^{i=m}$where $i = 1..m$
  - Experiment Bid: is the result of a random variation (in percentage) of the memory bid. The variation is uniformly distributed between 0 and 1.
    $MEbid_i^k = MBid_i(1 + Range)$ where $Range = (Variation)(Z)$ and $Z \hookrightarrow U(0, 1)$
  - Bidding position: is the couple price and quantity at which the Producer is willing to generate electricity at tick k.
    $\{EBid_i^k, Q_i^k\}_{i=1}^{i=m}$where $i = 1..m$
  - Profit up: is a sequence of information if the profit produced by a experiment bid higher that the memory bid. The size of the profit up is n.
    $\{ProfitUp_i\}_{i=1}^{i=m} = \{Profit \| MBid_i > EBid_i^k\}$ where $i = 1..m$ and $k = 1..n$
  - Profit down: is a sequence of information if the profit produced by a experiment bid lower that the memory bid. The size of the profit down is n.
    $\{ProfitDown_i\}_{i=1}^{i=m} = \{Profit \| MBid_i < EBid_i^k\}$ where $i = 1..m$ and $k = 1..n$
- **Rules:** The learning algorithm (probe and adjust see Algorithm 3.1 and Section 4.4) based on the average results of the profit.

$$\begin{cases} MBid_i^{t+1} = MBid_i^t(1 + Delta) & \text{if} \begin{pmatrix} AverageProfitUpMBid_i \\ > \\ AverageProfitDownMBid_i \end{pmatrix} \\ MBid_i^{t+1} = MBid_i^t(1 - Delta) & \text{if} \begin{pmatrix} AverageProfitUpMBid_i \\ < \\ AverageProfitDownMBid_i \end{pmatrix} \\ \left.\begin{matrix} MBid_i^{t+1} = MBid_i^t(1 + Delta) \\ MBid_i^{t+1} = MBid_i^t(1 + Delta) \\ MBid_i^{t+1} = MBid_i^t \\ MBid_i^{t+1} = MBid_i^t(1 + (Delta)(X)) \end{matrix}\right\} & \text{if} \begin{pmatrix} AverageProfitUpMBid_i \\ = \\ AverageProfitDownMBid_i \end{pmatrix} \end{cases}$$

where $X \hookrightarrow U(0,1)$

- **Consumers**

  The aggregated electricity demand of all consumers is represented in the Consumers agent. This agent does not react or interact, it just request for quantity of electricity independently of the price, hence there is not demand bid into the market. This means that the agent Consumers does not have rules, only states. Figure 6.6presents its states.

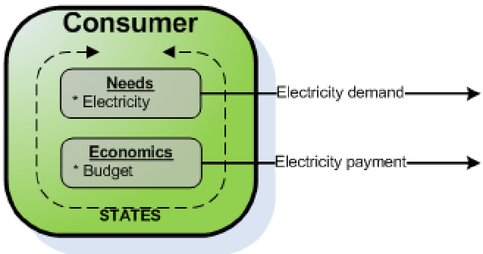


Figure 6.6: Consumer's states and rules

  - **States**: Consumers need electricity for their activities, and they have money to pay for it. Note that Consumers will always pay for their electricity consumption.
    - Demand function: function of the price (*ElectricityPrice*) consumers are willing to pay for the capacity (*ElectrityDemand*).

    $ElectricityPrice = 750 - (5)(ElectrityDemand)$

    - Budget: Consumers pay any price found in the clearing process, so they have illimited amount of money.

    $Budget \in [0; +\infty[$

6.2 Producers' Learning Algorithm

This section presents the learning algorithm which was introduced into the model.

The algorithm which establishes the bidding position of the Producers and is represented by a modification on the learning algorithm developed by Kimbrough and Murphy (2009).

The original Prove and Adjust algorithm was slightly modified in the following points:

- **Coding Modification**
  - The value of **epochLength**, or learning time, was determined and not fixed around 50 (see Section 7.3).
  - When the **AverageProfitUp=AverageProfitUp** then there are four cases[6] (see previous Section for further detail).
    - (a) The next bid positions will be higher than the current one.
    - (b) The next bid positions will be lower than the current one.
    - (c) The next bid positions will be the same as the current one.

[6] Kimbrough and Murphy (2009) mentioned restricted this case with the logic: **AverageProfitUp>=AverageProfitUp.**

· (d) The next bid positions will be random, either higher or lower than the current bid position.

The notation used in the Algorithm 6.1 is:

- **[]** indicates that the values to the left are emptied, in other words all the values are deleted.
- **ProfitUp** average of the profits obtained when the agent bided higher than its bid position (**MBid**).
- **ProfitDown** average of the profits obtained when the agent bided lower than its bid position (**MBid**).
- **AverageProfitUp** is the average of the profits obtained when the agent bided higher than its bid position (**MBid**).
- **AverageProfitDown** is the average of the profits obtained when the agent bided lower than its bid position (**MBid**).
- **epochLength** is equal to the memory need before making a decision, based on the results AverageProfitUp and AverageProfitDown.
- **episodeCounter** is a counter to establish how many experiments the Producer has done.
- *Range* refers to the percentage which the agent experiments with respect its bid position.
- *Delta* is the percentage of increase that the agent takes once the established whether to go up or down with respect its bid position.
- **EBid** is the experimental bid with respect the MBid.
- **MBid** is the price-bid position of the producer with which it makes some experiments.
- $U(0,1)$ stands for uniform distribution between 0 and 1.

Algorithm 6.1 Probe and Adjust's Pseudo-code (Kimbrough and Murphy, 2009).

1 : Set parameters *Range*, *Delta*, currentPrice, epochLength // Typically $Delta < Range \ll currentPrice$
2 : episodeCounter ←0
3 : returnsUp ← [] // Initialize returnsUp to an empty list
4 : returnsDown ← [] // Initialize returnsDown to an empty list
5: **Do** forever:
6 : episodeCounter ← episodeCounter + 1
7 : EBid ∽ U [MBid −*Range* , MBid +*Range*] // The agent's bidPrice is drawn from the uniform distribution within the range currentPrice ±*Range*
8 : Profit ← Revenue - Cost // The agent receives return from bidding EBid
9 : **If** (EBid ≥MBid) **then**:
10: ProfitUp← Profit
11: **else**:
12: ProfitDown ← Profit
13: **If** (episodeCounter mod epochLength = 0) **then**: // Epoch is over. Adjust episodeCounter and reset accumulators
14: **If** (AverageProfitUp > AverageProfitDown) **then**:
15: MBid ← MBid$(1 + Delta)$
16: **If** (AverageProfitUp < AverageProfitDown) **then**:
17: MBid←MBid$(1 - Delta)$
18: **If** (AverageProfitUp = AverageProfitDown) **then**:
19: (a) MBid←MBid$(1 + Delta)$
20: (b) MBid←MBid$(1 - Delta)$
21: (c) MBid←MBid
22: (d) MBid←MBid$(1 - (Delta)(X))$ // where $X \hookrightarrow U(0, 1)$
23: returnsUp ← []
24: returnsDown ←[]
25: **Loop** back to step 5.

6.3 Physical Network and Agents Configuration

This Section gives the most relevant details of the physical configuration of the system.

Producer and Consumers interact at the Sociosphere and Technosphere levels (see Section 5.1 and 5.1 for further detail) in a 3-node system. The node determines the placement where either Producers Consumers perform their actions (produce electricity and consume electricity respectively). The resistance of the lines, which determines the actual electricity flows are taken as equal (see Section 5.4for assumptions considered). Across this system configuration, the aggregated Consumers, Producer and the TSO interact.

The aggregated Consumers are represented by the demand function $ElectricityPrice = 1000 - (5)(ElectrityDemand)$, where $ElectricityPrice$ is the price consumers are willing to pay for the capacity $ElectrityDemand$.

All the Producers have generation plants with the same characteristics. This means that the generation plants have a maximum output 50[MW] and with the same cost (a fixed cost equatl to 15 [€/MW] and a variable cost of 10 [€/MWh]).

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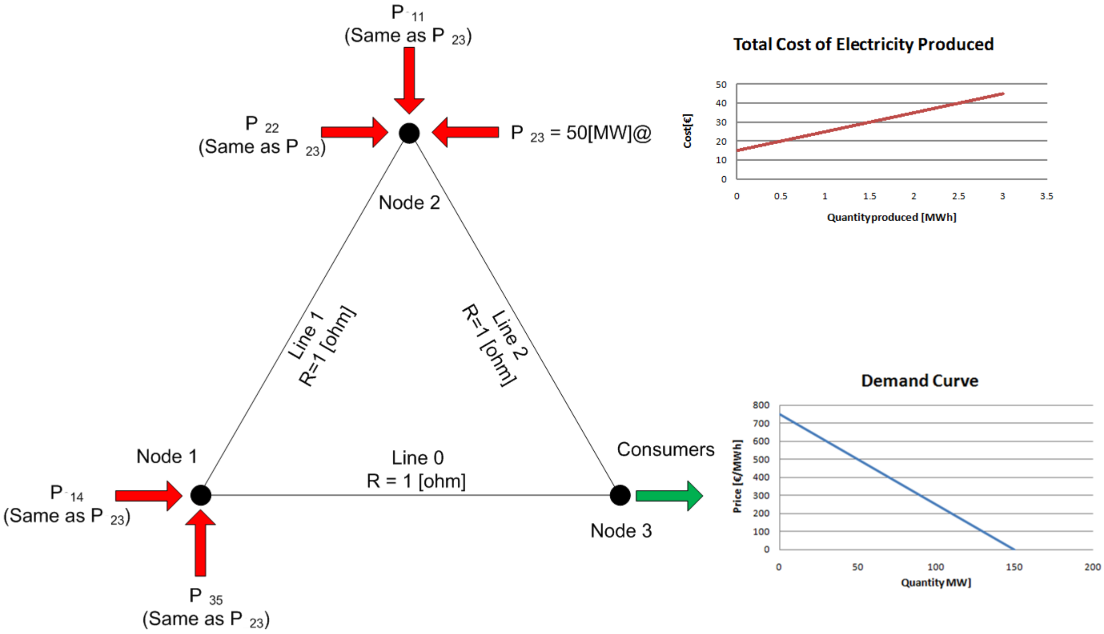


Figure 6.7: Network Configuration

6.4 Overall System Procedure

This Section explains by means of a workflow diagram and its correspondent algorithm, the Agent's activities undertake in the model.

Figure 6.8 depicts the general process that agents perform in the system, and Algorithm 6.2 represent in this activities in pseudo-code. Additionally, Appendix G presents the class diagram of the agents which was used to translated into Java language.

> The *Transmission System Operator* receives the demand of electricity from the *Customers* side while demanding the *Producers*' bid. The *Producers* based on their bidding strategy will respond and give their bidding position to the *Transmission System Operator*. With this information, the *Transmission System Operator* will clear the market are communicate the *Producers* who will produce electricity to meet the *Customers* demand in the merit order message. If there is a violation in the security limits of the interconnections, i.e. congestion, the *Transmission System Operator* is in charge to re-schedule the *Producers* which should produce electricity in order to avoid flow higher than the limit in each interconnector. This will imply that some *Producers* will be forced to shut down while other are commanded to produce electricity. The *Producers* will fulfil the *Customers* need of electricity by producing it, and the *Customers* will pay for this consumption. At the end the *Producers* will calculate the profit from the process.

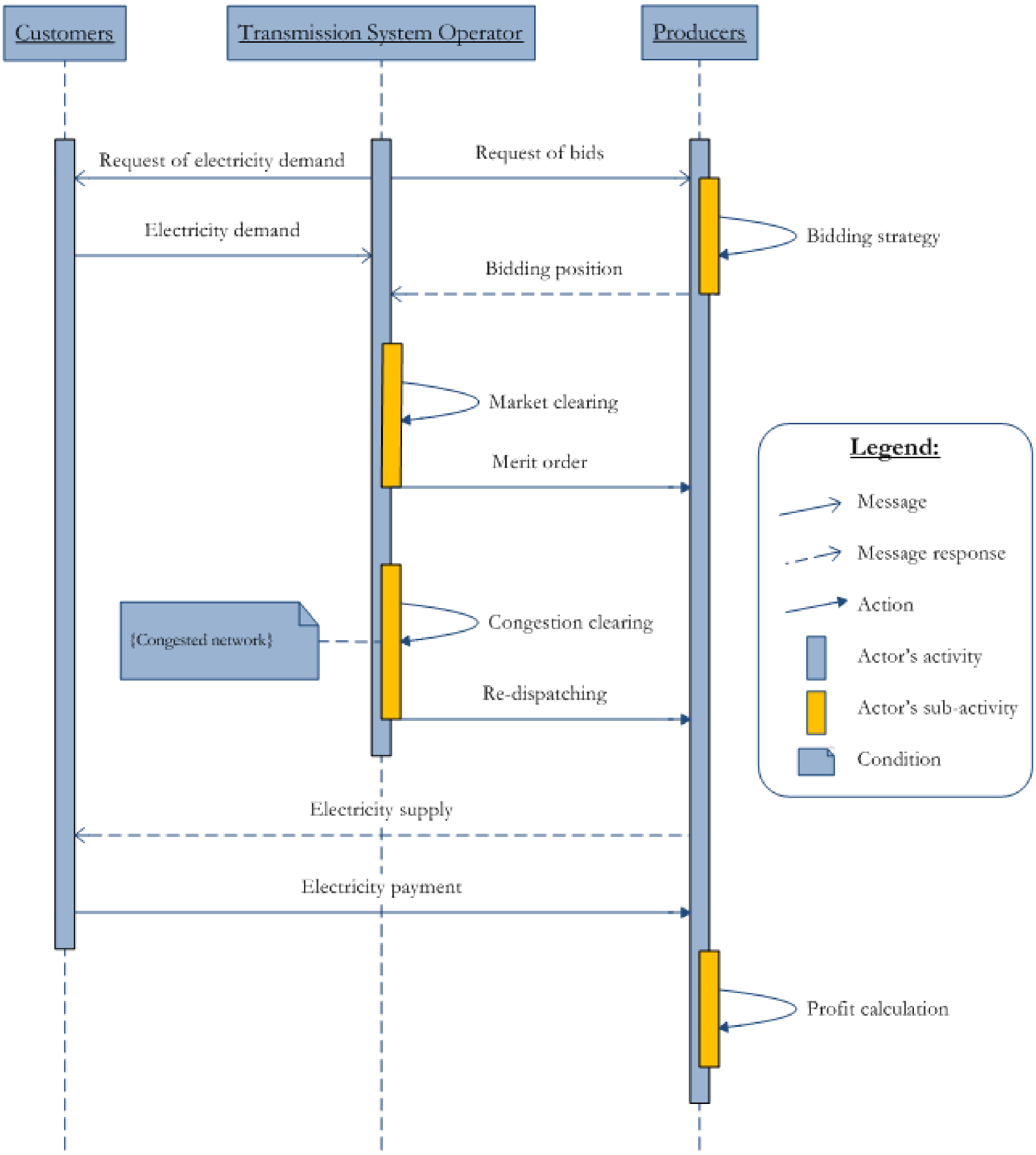


Figure 6.8: Re-dispatching process

The notation used in the Algorithm 6.2 is:

- **Cs** stands for Consumers,
- **TSO** stands for Transmission System Operator
- **Ps** stands for Producers

Algorithm 6.2 Re-dispatching procedure

```
0: Create Ps, Cs and TSO
1: t ← 0
2: TSO request electricity demand to Cs // Cs represent 1 agent
4: Cs send electricity demand to TSO
5: for i = 1 to n do // Ps represent n agents
6:      request bids of P_i // The P_i is a Producer i
7: end for
8: for i = 1 to n do
9:        P_i calculates its own bid position // See Algorithm 6.1
10:       P_i sends bid position to TSO
11:end for
12:TSO clears the market // See Section 5.1 for an explanation on market clearing process
13:for i = 1 to n do
14:       TSO sends merit order and market price to P_i
15:       P_i record its own result from merit order and price
16:end for
17: if congestino then
18:       apply re-dispatching // see Section 2.6 for an explanation
19:for i = 1 to n do
20:       P_i generates electricity
21:       TSO pay to P_i
22:end for
23:t ← t + 1
24:   goto 1
25: if t>=1000 then
26: stop run// see Section 6.5 for further detail
27: else if goto 2
```

6.5 Simulation Procedure

This Section explains the details of the modelling run and the software used to incorporate the algorithms.

Producers adjust their price position in the aim to maximize profits. However a Producer might never arrive to an optimal point since its outcome also depends on the other bidding position. In terms of computational time, the model was set to run first for 1000 ticks to see where there existed and attractor or not, and the spread of the data. Afterwards, the results where compared by running 10000 ticks and see if the previous result keep more or less the same. In case that 1000 ticks gave more or less constant results, the simulation was run 10 times to have a statistical information. In the event that 1000 ticks did not served to draw conclusions, or the values were not clear, the model was run for 10000 or even in some cases 100000 ticks.

The states, rules and interaction were translated into Java code, and the outcomes of different experiments were analyzed in Excel.

Experiments

The experiments are found based on the logic whether agent-based can give results for different assumptions at the agent level. The assumptions taken into account to form the scenario logic are:

- Agents quantity, i.e. Monopolistic case (1 Producer with 1 power plant) and the whole set (3 Producers with 5 power plants).
- Algorithm logic in case where the average profit up is equal to average profit down, i.e. $AverageProfitUpMBid_i = AverageProfitUpMBid_i$ where i is the tick.
- No congestion in the network vs. congestion.

The agents are the same in each scenario.

6.6 Output Values Analysis

In this Section, the most important variables from the model output are presented.

The different scenarios are analyzed based on different parameters which are compared with the underlying theory. The following parameters help to draw conclusions regarding the objective of this thesis and well to reveal important conclusion with respect the Probe and Adjust algoritm and some input data:

- **Electricity Price [€/MWh]**
- **MBid [€]**
- **Profit up [€]**
- **Profit down [€]**
- **Merit order [0;1]**

Criteria to Evaluate Strategic Bidding

Market power is difficult to identify in real life since information regarding power plants is private. However in this research, the model gives Producers cost plus variables of interest such as market price.

There are many indexes which aid the identification of the use of market power (Twomey, 2005). Indexes such as Pivotal Supplier Indicator (PSI), Residual Supply Index (RSI) and the famous Herfindahl-Hirschman Index (HHI), rely upon the market share of the generation plants. However in this research the market share is constant because producers do not expand or exit the market (given the short term focus), thus this indexes are not helpful.

The best comparison with respect the memory bid and the real cost of electricity production can be captured by the Lernex Index metric. It is defined as:

- **Lernex Index (LI) [0;1]** and defined as: $LI = \frac{P-MC}{P}$ where P is the electricity price and MC is the marginal electricity cost.

In either case, a perfectly competitive market is presumed to offer no margin above marginal cost, and hence the LI are zero.

6.7 Chapter Conclusion

The system levels: Emergent system, Network system and Agent system were translated into formal language.

The backbone of the system is the agent, which states and rules are:

Transmission System Operator (TSO):

- **States:** Information such as: the merit order, the cleared price and cleared output. The merit order is the list of Producers which are dispatched to produce electricity. The cleared price and cleared output are the price found in the market clearing process.
- **Rules**: The TSO has two rules clearing the market and clearing the congestion if it exits. Clearing the market means to match supply (Producers) and demand (Consumers). In case of re-dispatching, the procedure does not take into account the line capacities, and the network might be congested by means of the clearing the congestion rule.

Producers

- **States:** Each Producer calculates its profit and establishes its bidding position. The cost function depends on the technology and represents the cost to produce electricity, in other words the fixed and variable cost.
- **Rules:** Producers bid either going up or down of a bid position. This rule is the learning algorithm introduced by Kimbrough and Murphy (2009).

Consumers

- **States:** Consumers demand electricity and pay for it independently of its price.
- **Rules:** Consumers are passive entities which do not adapt or self-organize. Thus there are no rules

Additionally, information regarding the physical constraints of the network and generators power plants, were introduced into the model. The experiments were built taking into account:

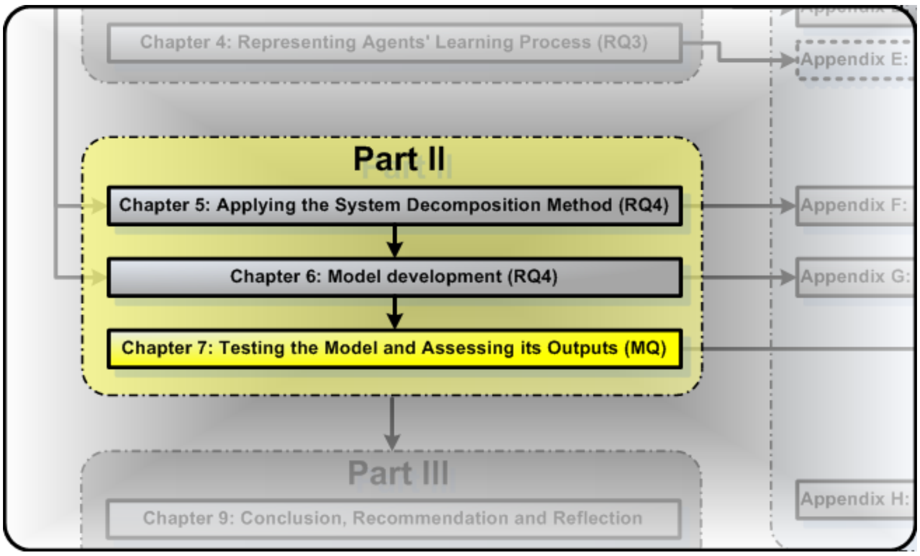
- Agents quantity
- Algorithm logic in case where the average profit up is equal to average profit down.,
- No congestion in the network vs. congestion.

From the experiment outcomes, the variables which were analyzed are: Electricity Price [€/MWh], MBid [€], Profit up [€], Profit down [€], and Merit order [0;1].

The Lernex Index is select to capture the possible exercise of market power because there is access to the Producers' cost, which in reality might not be accessible.

Chapter 7

Testing the Model and Assessing its Outputs



This Chapter addressed the MQ. First the confidence is built by testing the model consistency (Section 7.1) and checking that the objectives of the study should be met by the model's outputs (Section 7.2). Second the most interesting results found are exposed in Section 7.3.

7.1 Verification

This section presents the procedures to determine whether the model was correctly coded, an it represents the system.

The objective is to check whether the model has been coded correctly and consistently (Erick et al., 2008). Verification answers the question: "Does the model do what I wanted it to do?", in other words it assesses whether the code has been correctly been implemented for the purpose of the research.

In agent-based modelling, agents' interaction results in the emergent behaviour (Holland, 1999). The interactions are non-linear and the global behaviour cannot be found based on the sum of all isolated agent's behaviour. Therefore, the verification has to start in the unit block of agent-based, i.e. the agent; followed by the verification of the cooperation and coordination of agents, i.e. the interaction. Models are verified at three levels:

Single-Agent Verification The behaviour of each agent is separately verified from the rest of the agents.

Minimal Model Interaction Verification The interaction of a agents' set, composed with the minimal agents, is tested.

Multi-Agent Verification The overall behaviour, caused by the interaction of all the agents is verified.

Single-Agent Verification

The agents are the basic component in Agent-Based modelling, so the first step is to check single agents (no interaction with other agents is performed). Since there are 3 types of agents (Producer, Consumer and Transmission System Operator), the single-agent verification test will be run 3 times.

Equation Check

The equations formulated inside all the variables were assessed so as to know the function range[1]. Each equation was isolated and traced backwards to know its origin and the link with other equations. All the equations inside a variable are a formalization of the case description. In some cases the formulas are bounded so as not give illogic results.

For example the experimental bid $MEbid$ are restriction to a range between 0 [€/MWh] and 200 [€/MWh] since the maximum demand correspond to 200 [€/MWh] and negative bids are not acepted. Thus the formula introduced is:

$MEbid = MIN(MAX(MEbid; 0); 200)$

Dimensional Analysis Test

The units of all the variables used in equations were checked so as attain the left hand side of the equation equal to the right hand side in terms of units. All the units of the variables correspond to factors encountered in reality.

For example when calculating the revenue of a Producer as:

$Revenue = (clearedPrice)(maxCapacity)(meritOrderProducer)$

[1]The range is referred to the values that could be introduced and the values that could give the formula.

Where *clearedPrice* is measured in [€/MWh], the *maxCapacity* in [MW] and the *meritOrderProducer* is unitless. Then the *Revenue* will be in [€/h] indicating the amount of money the Producer receives for producing an amount of electricity in a period of time.

Theoretical Prediction or Sanity Check

This methods test whether known inputs introduced to the agent, will produce expected theoretical outputs. A difference between the expected and the real outcomes indicate a fault at the coding level. Thus the pseudo-code and the code (entered into the agent) are compared to determine if whether the origin of the error is a logical error in the pseudo-code, or a practical implementation error.

The basic assumption of the model is that agents learn from their past experimentation, so if there is no learning (EPochlength equal to one tick) the agent will not arrive to the optimal point to maximize its profit. In other words it will experimentate and will not make any logic decision. Figure 7.1 depict one of this case in which a value equal to 40 [€/MWh] was established as the cap to avoid higher values [2]. It can be seen that the Producer bid seems a random walk, with no memory. These result can be contrasted with Figure 7.2 where the monopolist arrives to the optimal price bid.

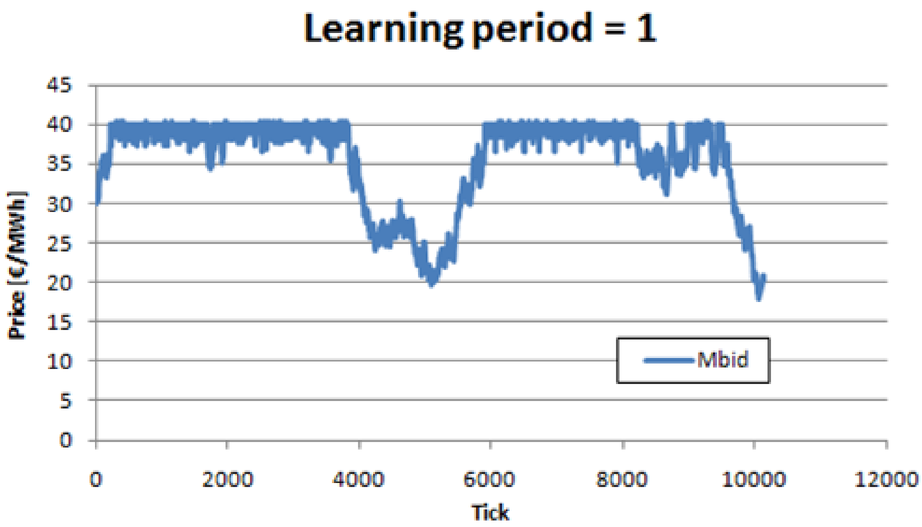


Figure 7.1: No learning for Monopolistic case.

Breaking the Agent

Parameters or series of parameters which crash the agent (for example a division by 0) are sought in this test. The parameter(s) found might not be an error but a limitation in the code, so the agent(s) or situations which can generate this breaking value are established in order to prevent a break in the agent.

For example in the re-dispatching methodology, the TSO has to seek which Producers are causing the congestion while being in the merit order. Since The not all Producers cause congestion, nor all are inside the merit order, the agents were assigned with a number between 0 and

[2]Although in the complete model the cap was set to 200 [€/MWh], in the case of monopolistic competitions the cap was 40 [€/MWh] for ilustration purposes.

1 when they were inside the merit order and establishing their influence in the overall electricity network based on their position (see Section 5.1). Then the TSO can seek for agents with this combination, i.e. merit order higher than 0 and causing congestion.

Minimal Model Interaction

In this test, the model is run with the minimal agents needed to run the model (minimal in terms of agents' interaction). The basic interactions are checked whether they occur as they are intended.

For the European Wholesale Electricity Market system (see Section 5.1 for description) the simplest case is in case of only 1 Producer and Consumers, i.e. a monopoly. This setting can be compared with theoretical results from basic economics in which maximizes the monopolist profit. The details of the optimal point in which the monopolist maximizes its profit can be found in Appendix E.

The optimal theoretical price at which the profit is maximized is 25 [€/MWh]. This point is reached by the monopolist starting from any initial value (between the range of 0 and 40) but the convergence depends upon the Delta[3] and the EPochlength[4] values as Section 7.3 and indicates respectively. Figure 7.2 depicts a run made with an initial value equal to 10 [€/MWh] with an learning period (EPochlength) equal to 20 and a Delta of 1%.

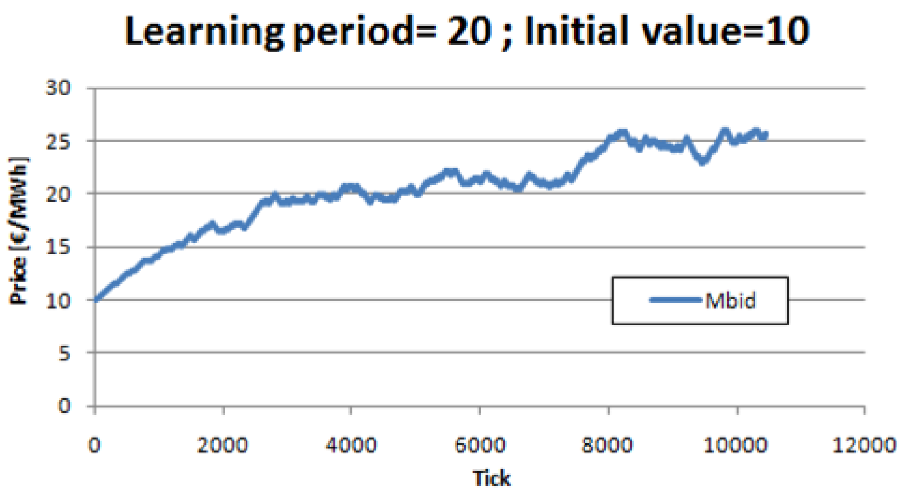


Figure 7.2: Optimal monopolistic bid price convergence.

Multi-Agent Verification

All the agents which compose the system are implemented in the model run and the emergent pattern in the model is tested.

With respect to the *European Wholesale Electricity Market* system, the difference between the minimal and the total amount of agent, is the quantity of Producers. So in this test, the

[3]The Delta value is the percentage that Producer increments of reduces its price bid, see Section 4.4 for further detail.

[4]EPochlength is the number of tick before the producer takes a decision whether to bid higher or lower the next round, see Section 4.4for further explanation .

quantity of Producers is increased to 3 with a total number of 5 power plants, while there are 1 Consumers and 1 Transmission System Operator.

Timeline Sanity

In this point, the patterns which resulted from the simulations, under different parameter settings, have to be fully explained. Any pattern or part of it which cannot be understood, will give as result that the understanding of the system has not been captured.

For example the model was run in case of congestion, solved by re-dispatching (see Section 2.6), and the learning rule was to go up in case that the average profits bidding up were equal to average profits bidding down (see Section 6.2for further detail on the algorithm logic). The development of the average price-bid is depicted in Figure 7.3.

The Producer increased its bid position since regardless of its bid, it received money from the TSO since it was a must-run plant (like in the case of Producer 1 in Figure 2.3). Hence the increase was smooth as the TSO needed the Producer to supply electricity. The smooth increase was interrupted because this Producer was not the only one which was needed to generate electricity, but another one was as well a must-run plant. Around the 10000 tick, the Producer start to bid lower, because its bid was higher than other Producer, and because it was the most expensive power plant and no more that the maximum capacity of other Producer was needed, the Producer has to decrease its price bidding position.

The dynamic of the bidding process and the fact of congestion, created the need of a must-run plant which in general increased its bid position up to the cap imposed to 200[€/MWh]. The lernex index rapidly increased towards 0.95 which is maximum value[5] as Figure 7.4 indicates. This means that the Producer exerted market power[6] since it bid different from its marginal cost.

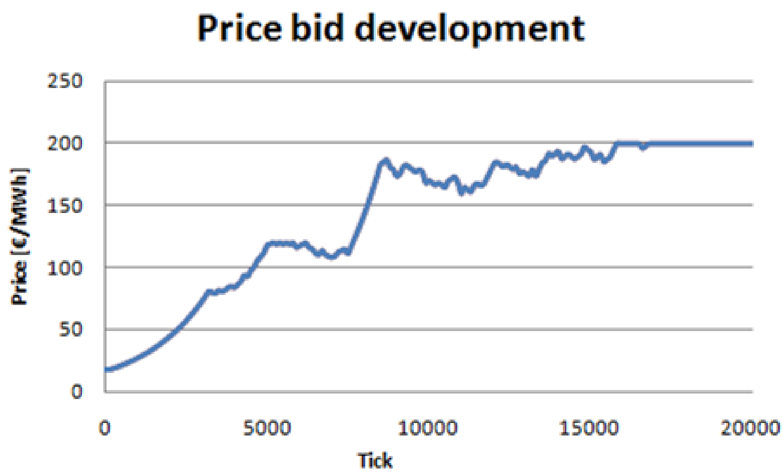


Figure 7.3: Price development for Producer out of merit order bidding in case of congestion.

[5]Since the lernex indes is defined as: $LI = \frac{P-MC}{P}$ where P is the electricity price and MC is the marginal electricity cost. The maximum price which producer can bid or cap is 200[€/MWh], and the marginal cost is 10[€/MWh], thus $LI = \frac{200-10}{200} = 0.95$

[6]Note that market power is refered to offer a price different from the marginal cost. An in terms of the Lernex Index, if the LI is different from 0, then there is market power (see Section 6.6).

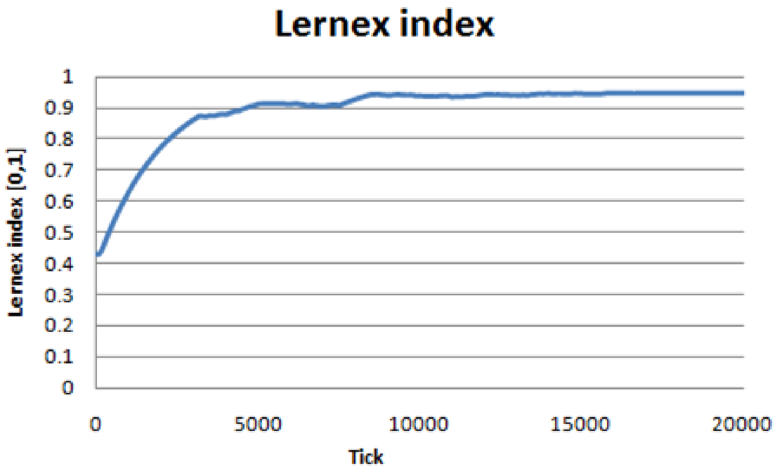


Figure 7.4: Lernex index for Producer out of merit order bidding in case of congestion.

7.2 Validation

This section presents the summarized results of validation to test whether the results from the model are as expected.

The objective of validating a system dynamic model is to see if the structure is adequate on the basis of the research objective (Erick et al., 2008). The validation is generally done by performing experiment in the model. Since Agent-Based in an approach with qualitatively analyzes the data on the basis of quantitative output, validation test should focus on the pattern of interest, i.e. in the price-bid of Producers.

Comparison with Accepted Theory

The case of the monopolist was already proved in which the model converged towards the optimal price which maximizes its profit (see previous Section) . For the case of duopoly, the model gave the Cournot equilibrium for the marginal Producer, whereas the other Producer kept its price-bid lower so as to be inside the merit order.

Sensitivity Analysis

Understanding which factors affect the system and how they influence the behaviour are goals traced in this test. The test identifies the variables which can be used as policy parameters, i.e. parameter in which the values can be modified by the problem in the real system and produce an effect on the system (Erick et al., 2008), or parameters which need attention when being estimated since they produce a greater change in the system than other ones.

Variables such as generation cost and power plants capacity influence the clearing price and outcomes, but they are not of interest since do not directly influence the rule to exercise market power but they influence the optimal point to maximize profits.

The variables which directly produce a significant effect on the learning process are the learning time and the incremental memory bid positions (see Section 7.3).

7.3 Interesting results

This Section presents the most interesting results found in the model. The monopolistic case is carefully explained because it is easier to understand and to compare with optimal values as seen before. As well, important results were found in this case which were used when the model incorporated more agents.

Monopolistic Case

While running the model with the minimal agents needed (1 Producer, 1 TSO and the aggregated Consumers), important results of the variables inputs where attained. There exist a great effect in the Delta and EPochlength values which represent the incremental memory bid position and the learning time respectively.

Incremental Memory Bid Position

The incremental modification of the memory bid a producers makes is represented as the Delta value (see Section 4.4 for further detail). While running the

The simulation where run with a EPochlength value equal to 20 and an initial value of 35 to see whether keeping everything fixed, the effect of the Delta in the amount of ticks needed to converge towards the optimal value. The Figure 7.5 presents the run of the simulation with a Delta of 0.1%. The Figure 7.6 presents the run of the simulation with a Delta of 1%. The Figure 7.7 presents the run of the simulation with a Delta of 10%.

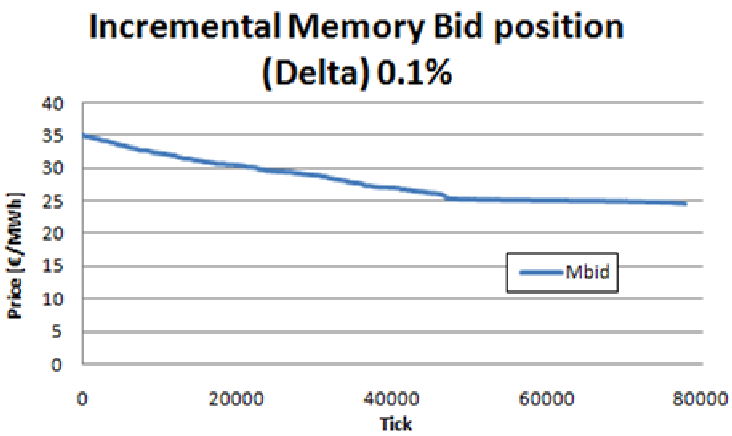


Figure 7.5: Delta of 0.1%.

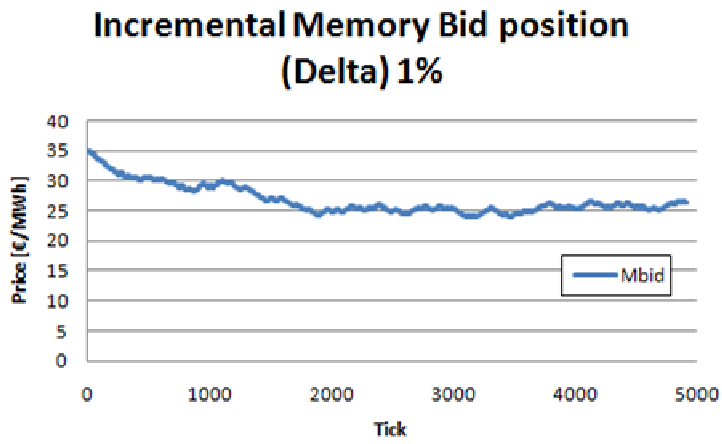


Figure 7.6: Delta of 1%.

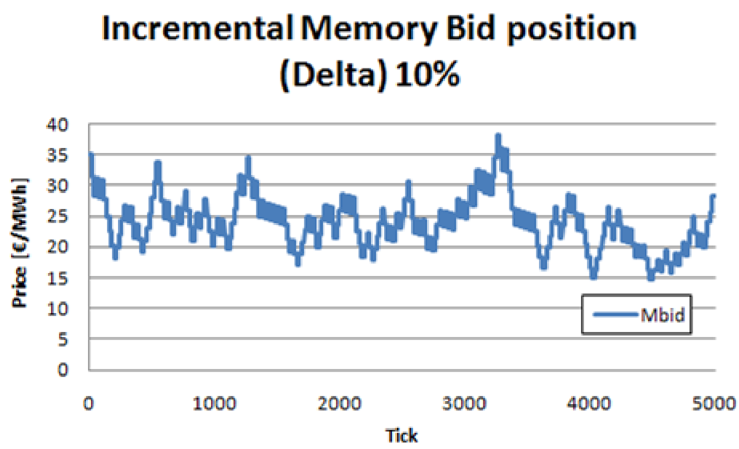


Figure 7.7: Delta of 10%.

If the Delta has a value of 10%, there is not a real convergence into the optimal value. In the case of Delta equal to 0.1% the convergence is quite smooth but the amount of tick need reaches around 50000, this implies that more time is needed per run. Therefore a trade-off has to be made, between convergence time and certainty (in terms of where arrived to an attractor or not).

For next simulation runs, the value of Delta was set to 1% because it gave a good take-off result between converge time (measuered in ticks) and the smoothness of the converge pattern (measured in standart deviation).

Learning Time

The learning time (or EPochlength) refers to the amount of time an agent need to make experiments, before taking a decision to adjust its bid the next round. Adopting a value of Delta equal to 1%, the value of EPochlength was variated to measure its effect in the convergence tick.

Three experiments were performed variating the EPochlength value (10, 20 and 30) and each experiment run 10 times to have the spread values. Figure 7.8 summarizes the outcomes of the experiments. Note that the tick to convergence axis on logaritmic scale since values diverted largely between them. Once again, there has to be a trade-off between tick to converge and the spread of results. Given that in the case of running the model with an EPochlength with a value of 30 took around 10 minutes each run, and only one Producer was interacting with the TSO, the value of EPochlength equal to 10 was adopted to prevent long run in the case of three Producers.

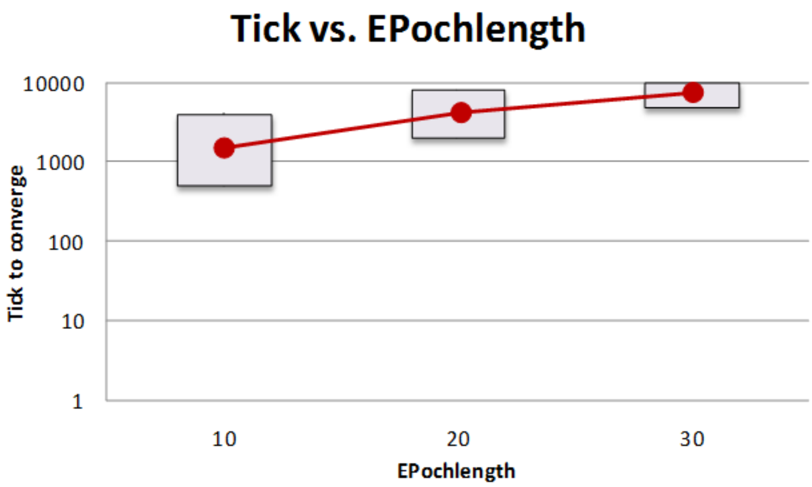


Figure 7.8: Tick and EPochlength in case of Monopoly.

Optimal convergence

Assuming that the consumer have a demand curve equal to $ElectricityPrice = 40-(0.2)(ElectrityDemand)$, where $ElectricityPrice$ is the price consumers are willing to pay for the capacity $ElectrityDemand$ and the monopolist have the $TotalCost = 15 - (10)(ElectrityProduce)$ where 15[€] is the fixed cost and 10[€/MWh] the variable cost, the profit will have a maximum at the price bid of 25 [€/MWh]. The Producer will try to this point by starting in any point between 0 [MW] and 50 [MW]. Figure 7.9 present the case how the monopolist arrives to the optimal point based on the Probe and Adjust algorithm (see Section 4.4 and 6.2 for further detail into the algorithm). The Producer (monopolist) could start with either a lower or higher value than the optimal price (see top-left and top-right side respectively of Figure 7.9):

- In case that $MBid$ is at the left of the optimal point (see top-left side of Figure 7.9): The Producer makes experiments around $MBid$ and this result in different experimental bids$EBids$.
  $EBid_1$and $EBid_3$ are higher than $MBid$, whereas $EBid_4$, $EBid_5$ and $EBid_6$ are lower than $MBid$. The average profit of the $EBids$ higher than $MBid$ are higher than the profits of the $EBids$ higher than $MBid$, in other words $AverageProfitDown < AverageProfitUp$. This implies that in average it was better to bid higher than lower and the next move should be somewhere higher than $MBid$. If the Producer bids higher, then he will be approaching the optimal point where the profit is maximized.
- In case that $MBid$ is at the right of the optimal point (see top-right side of Figure 7.9): The Producer makes experiments around $MBid$ and this result in different experimental

bids$EBids$.
$EBid_1$and $EBid_2$ are higher than $MBid$, whereas $EBid_3$, $EBid_4$ and $EBid_5$ are lower than $MBid$. The average profit of the $EBids$ lower than $MBid$ are higher than the profits of the $EBids$ higher than $MBid$, in other words $AverageProfitDown > AverageProfitUp$. This implies that in average it was better to bid higher than lower and the next move should be somewhere lower than $MBid$. If the Producer bids lower, then he will be approaching the optimal point where the profit is maximized.

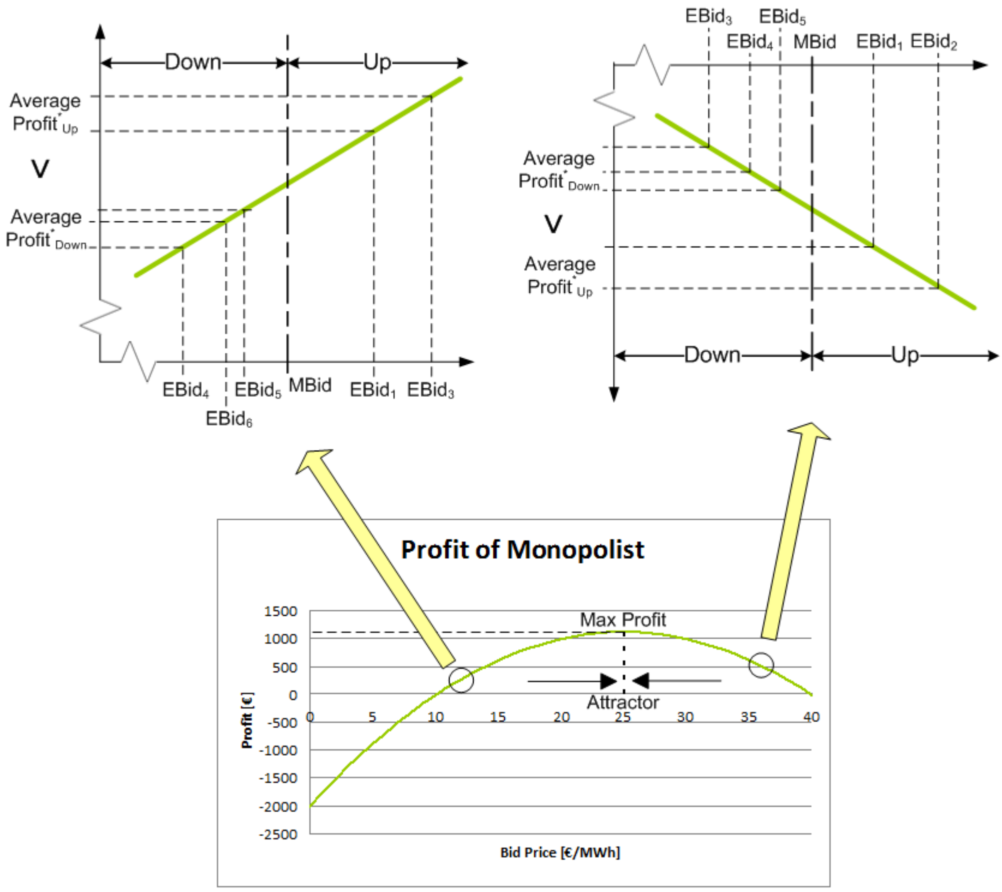


Figure 7.9: Monopolistic optimal point convergence.

Overall system

This section presents the effect on the results obtained when the learning algorithm logic when either bidding up or down gives the same results.

When supply and demand are matched, the Producers which are inside the merit order receive the same price to generate electricity. This means than if they bid lower or higher, their profit will be same up to the marginal Producer's bid. This implies that the average profit up is equal to average profit down. For different cases where analyzed in other to identify the consequence when **AverageProfitUp=AverageProfitUp** (see Section 6.2for detail on the rules).

- If the rule is to increase the bid position, then Producers outside the merit order exerted market power as seen before. The Producers inside the merit order raise their bid up to the point where they might be outside the merit order, and hence the overall electricity price increased.
- If the rule is to decrease the bid position, then Producers inside the merit order tended to bid as low as possible since they get a unique price. But the Producer outside the merit order did not take advantage of being a must-run power plants, i.e. a power plant needed in case of congestion.
- If the rule is stay the same or to randomly choose, the Producers inside and outside the merit order did not significantly move from their position.

In summary, the model should have both rules, increase the bid position and decrease the bid position to Producers which are outside and inside the merit order respectively.

7.4 Chapter Conclusion

The model passed the verification and validation test, proving to be a robust and reliable model. The model reproduced theoretical monopolistic and duopoly (Cournot competition) optimal prices. The results obtained indicate that parameter such as the learning time and the incremental bid which agents assume, have to be carefully chosen. The learning time refers to the amount of time an agent needs to make experiments before taking a decision to adjust its bid the next round, and the incremental bid is the percentage of adjustment that the agent takes after the learning period. The effect of this parameter, operationalized in terms of computational time to achieve the equilibrium and standard deviation of the results, indicated that:

- The higher the learning time, the higher the time computational time and the lower the standard deviation.
- The higher the incremental bid, the lower the computational time and the higher the standard deviation.

Therefore, trade-off needs to be done when choosing the learning time that an agent needs to take a bidding decision (go up or down of its current bid) so as converge to the theoretical optimum. The parameter should be carefully tested because in some cases the standard deviation was so high, that the convergence was never achieved.

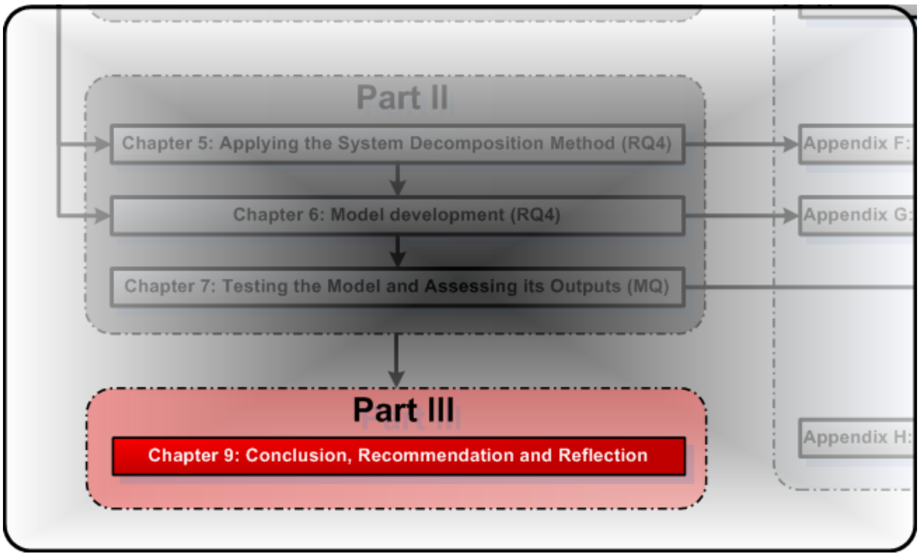
The case where the profits are the same bidding higher or lower than the bid position proved to have an interesting effect on the results. While bidding up the Producers outside the merit order strategically bid, when bidding down these Producer do not take advantage of their characteristic of being a must-run power plant. However, when Producers inside the merit order bid up the overall electricity price increases, and in case these Producers bid down they secure their position since they get the same price. Therefore, the model should have both rules, increase the bid position and decrease the bid position to Producers which are outside and inside the merit order respectively.

Part III

Conclusions

Chapter 8

Conclusion, Recommendation and Reflection



This chapter aims to answer the research questions, recommend the future research and give an analysis of the work performed. First a brief background of the issue is present followed by a general overview. Section 8.1 draws the conclusion with respect the objective and research questions. Next, Section 8.2 undertakes some ideas to extend this research. Finally, Section 8.3 captures the experience of this thesis project and proposes some suggestions for future researchers.

Introduction into the Issue

In many cases, congestion is a recurrent problem that exists in electricity lines since the demand, in general, steadily increases whereas lines capacity cannot increase in small increments but only in multiple units of line capacity. Congestion in electricity lines hampers the interconnection of local markets because the interconnection line capacity is lower than the optimal. Hence it limits the European Union goal to form a unique electricity market while liberalization is spread. Moreover, congestion could jeopardize the benefits of liberalization, like it happened in California and in England, where Producers manipulated the market by bidding strategically, in other words, they withheld capacity and/or offered higher prices than marginal cost. A better understanding of the new liberalized electricity market in order to support decision-makers to formulate sound policies is thus needed. Given the complexity of these markets, simulation seems to be a promising tool to provide an understanding thereof.

Thesis Overview

The following thesis started with an introduction of the issue with relevant literature in order to gain a theoretical understanding. The survey encompassed economical, modelling, congestion mechanisms and policy related theories. An assessment of the system *European Wholesale Electricity Market* indicated that it is a Complex Adaptive System, in other words it *emerged* as a consequence of the dynamic *interaction* of many heterogeneous market players. After reviewing possible paradigm approaches, Agent-Based modelling was select given its *purpose, object* and *methodology* correspond to the objective of the research and the system description. On the basis of this approach, the system was described and translated into machine-readable Java codes which were introduced into Repast. The confidence on the model was established and interesting conclusions were drawn from the model's results.

8.1 Addressing the Objective and Research Questions

Objective The objective of this thesis is to gain an understanding of the producers' strategic bidding process in congested lines by means of a simulation model.

The objective was reached with the construction of an agent-based model. The model captures the main interactions in the wholesale electricity market which uses a re-dispatching as congestion mechanism.

The main research question this thesis undertook is:

(MQ) How could market power, in the case of congested electricity lines be modelled?

This sub-question was addressed in Chapter 7. Firstly the model was tested to check whether it could reflect the systems and secondly the results of the model were analyzed.

It was demonstrated that by means of agent-based simulation paradigm, agents can learn how to strategically bid in electricity markets. The agents use a simple learning rule denominated Probe and Adjust proposed by Kimbrough and Murphy (2009). The learning rule is a trial-and-error approach which, based on limited previous experience indicate the agent whether to bid higher or lower than the bid the agents has been bidding. The model reproduced theoretical monopolistic and duopoly (Cournot competition) optimal prices. However, values such as the learning time and the incremental bid which agents assume, have to be carefully considered because they have a significant effect on the results like the monopolistic case showed. The learning time refers to the amount of time an agent needs to make experiments before taking a decision to adjust its bid the next round, and the incremental bid is the percentage of adjustment that the agent takes after the learning period. The effect of this parameter, operationalized in terms of computational time to achieve the equilibrium and standard deviation of the results, indicated that:

- The higher the learning time, the higher the time computational time and the lower the standard deviation.
- The higher the incremental bid, the lower the computational time and the higher the standard deviation.

Therefore, trade-off needs to be done when choosing the learning time that an agent needs to take a bidding decision (go up or down of its current bid) so as converge to the theoretical optimum.

Another important aspect is the rule when the average profit up is equal to average profit down. This apparent minor detail, proved to have a bid impact in the results, since given the unique auction price settlement arrangement of the electricity markets, agents usually have states in which bidding higher or lower does not produce a change in profit.

For the event of congestion, the bids Producer submitted, were largely different in comparison of bids without congestion if the rule when average profit up were equal to average profit down, was to go increase bid. The producers learn increase their bid price and exert market power. However if the rule when average profit up were equal to average profit down was to go down or keep position, the result were no statistically different from the case of no congestion.

This result indicates that two rules should be applied in the model when considering strategic bidding in congested lines: (1) agents which are within the merit order should bid lower when the average profit up is equal to average profit down; and (2) agents which are within the merit order should bid higher when the average profit up is equal to average profit down.

The main research question led to the following sub-questions:

- **(RQ1) What are the most important mechanisms to solve congestion as seen in the European Wholesale Electricity Markets?**

Chapter 2 undertook this sub-question. The European Commission showed its preference for market-based method in the Regulation (EC) No 1228/2003, corroborated in the amending presented in 2006. The idea is that the market can provide the correct allocation of the interconnection capacity, enhancing the competition among market players and increasing the liquidity of the markets where the capacity is allocated. To this end, the Member States can choose amongst market splitting, market coupling or explicit auctions; however nodal pricing does not represent a good solution because of external flows of neighbouring Member states distorts the price at the nodes in the local market. Independently from the selected method, the Member States should adopt an alleviation method (remedial actions) to cope with congestion.

An alleviation mechanism, or real-time method, clears congestion by modifying the generation after the market clearing process. It can be used in real time markets if congestion has to be relieved immediately or in markets in which no allocation mechanism is used. Re-dispatching and counter trading are two alleviation mechanisms commonly used, from which counter trading is essentially the same as re-dispatching.

Re-dispatching is a mechanism which after the market clearing process has taken place, reschedules the power plants. The Transmission System Operator needs to co-ordinate the shifts of power plants (re-dispatch) up to the point the flow matches with the line's capacity. First the most expensive is curtailed and if even shutting down this plant does could not solve congestion, the next most expensive power plants is curtailed. All the power which was reduced have to be replaced by other power plants which produce flows within security limits. However, the price at which the re-dispatched power plants are willing to generate electricity is higher than the clearing price; and curtailed power plants will receive a payment for not produce electricity that puts the network in risk.

- **(RQ2) What is an adequate modelling paradigm to simulate the producers' market power?**

This sub-question was addressed in Chapter 4. Since market power is regarded as a strategy a Producer adopts to increase its profit by any means other than lowering its costs, the Producer needs to adapt and establish its position. This means that Producers learn how to bid into the market so as to maximize their profits into the electricity markets. Electricity markets are under co-evolution and they are regarded in this thesis, to emergence from the interaction of Consumers who want electricity and Producers who want to sell electricity.

The possible simulation paradigms which can be used to represent the electricity system and obtain useful results are basically Discrete Event simulation (DE), System Dynamics (SD) and Agent-based modelling (AB). Individual behaviour is hard or even impossible to capture with DE and in the case of SD the behaviour is aggregated. On the other hand, AB assigns individual behaviour and observes the emergent behaviour out of the interaction of a population of those agents. Moreover, the global system behaviour is explicitly defined and remains constant throughout all the simulation in SD and DE, whereas in AB it emergence as a consequence of interactions. Therefore, AB is aligned with the system characteristics and with the purpose of this research.

- **(RQ3) What is a useful algorithm to describe agent learning behaviour?**

This sub-question was addressed in Chapter 4.

A learning algorithm considers adaptive behaviour of goal-oriented players who may not be rational. Examples of learning algorithms used in agent based are: reinforcement learning, Q-learning and Probe& Adjust.

Agents using reinforcement learning either increase, decrease, or repeat their last bid depending whether profit targets have been met in the last round or not. With Q-learning, an expected reward is introduced into the algorithm. With Probe and Adjust algorithm, the agents learn through trial-and-error. From these learning algorithms, Probe and Adjust is selected given that Producer might have limited rationality to make good estimates of the future, and will not remember all the information from the past.

The Probe and Adjust algorithm proposed by Kimbrough and Murphy (2009) aims to capture the learning process by which an agent learns through experimentation, a trial-and-error methodology. Basically the agent makes small increments going up or down on their bids based on previous results every certain period of time. This period of time represent the time an agent need to make a decision.

- **(RQ4) What are the characteristics of the market players' states and rules?**

The market player's states and rules are determined and formalized in Chapter 5 and 6 respectively. By means of the system decomposition methodology, 3 different types of agents were identified to represent the main market player in electricity markets. The agents are: *Producers*, the *Transmission System Operator (TSO)* and the *Consumers*. All the agents have states and rules where the states are attributes of the agents and rules are decision logics which depend on the agent's states and inputs.

Transmission System Operator (TSO) has to manage the market and manage the network (like in the case of centralized markets).

- **States:** The rules that the TSO undertakes give as result: the merit order, the cleared price and cleared output. The merit order is the list of Producers which are selected to meet the Consumers demand for electricity. The cleared price and cleared output are the price which all Producers receive for generating electricity and the total electricity production respectively.
- **Rules**: The TSO is in charge of managing the market and the network. The former task involves clearing the market and the latter to clear congestion if it exits. Clearing the market means to match supply (Producers) and demand (Consumers), in other words the most economical efficient power plants are dispatched to meet the consumers who value electricity the most. If the procedure does not take into account the line capacities, the network might be congested and should be cleared. Clearing the congestion means to apply a re-dispatching as congestion mechanism.

Producers strive for maximizing their profit and may exercise market power to extra profit.

- **States:** Each Producer needs to calculate its profit and establish its bidding position. To calculate the profit, the Producer needs its cost function and all the information that the TSO publishes, i.e. the merit order, the market price and market output. The cost function depends on the technology and represents the cost to produce electricity, in other words the fixed and variable cost.
- **Rules:** Producers make small increments going up or down based on previous results every a fixed amount of time. This represents the amount of time needed to make a decision. The Producer's bid position establish the reference to the experiments bid up or bid down. The decision logic is to go up (down) if the results indicated that bidding up (down) gave him a better result in comparison with bidding down (up).

Consumers represent an aggregate demand for electricity of all consumers (small and large consumers).

- **States:** Consumers demand electricity and pay for it independently of its price.
- **Rules:** Consumers are passive entities which do not adapt or self-organize. Thus there are no rules.

8.2 Recommendations for Further Research

This thesis traced a small step into the possibilities that agent-based modelling can offer to analyze strategic bidding in congested electricity lines. Important conclusions and insights were gained, but there is still work to be done in the future.

From the assumption taken, one interesting next step could be to is to incorporating balancing markets in the system. This will allow the direct trade of electricity without going to the market. Consumers and Producers might hedge the risk of high and low prices respectively. Although this might involve a high computational challenge since both, Producers and Consumers should bargain electricity parallel to the bidding procedure.

Other interesting insight could be gained by modelling Consumers active rather than passive. Active in the sense that they can as well adjust their bidding position as Producers do. This expansion could gave important insights of the strategy and learning process that both, Consumers and Producer have in case of congestion being both active. Although in the short term in reality, the demand is almost inelastic (as assumed in this thesis) meaning that Consumers do not really react to a change in the electricity price, in the long-term there should be a reaction to an increase in price; for example Consumers might replace its consumption from the grid for own electricity generation.

From the conclusion, it seems that unique auction price results in situations where Producers get the same if they bid up or down. For example if the Producers is in the merit order and in not the marginal generator, if it bid higher or even 0, it will get the market price. To this extent, an interesting extension of the model would be to proof if Producers bid marginal cost under alternative discriminatory auctions. Since every Producers gets what it bided if it is in the merit order, it seems logic that Producer will not bid lower, since they will not recover the generation cost; or they will not bid high because they could be outside the merit order. This reasoning should work in case of no congestion. But in case of congestion, the some must-run Producers should learn to strategically bid because they are needed to keep the system within security limits.

Due to time constraints, only re-dispatching were analyzed, however introducing other congestion mechanisms would give the possibility to explore the difference in results for each congestion mechanism. What would be quite interesting, is to have a system with allocation and alleviation mechanism. For example use zonal pricing and re-dispatching mechanisms like is done in Sweden.

If the future researcher extends the model by any of this propositions or in other direction, it is advisable to introduce an ontology given the amount of interactions amongst agents will increase and may get more complicated. And by means a language shared amongst agents, the ontology, the interaction would be simple to code.

8.3 Reflections

This Section aims to analyze the main aspects of the present thesis, present some impressions and possible give some guideline for future researchers. Firstly it provides an assessment of the process which was undertook in this thesis. Secondly some thoughts regarding the modeller are present.

Reflections on the Process

A research is the search for a solution of a problem which can be tackled in different manners. The researcher is in charge of choosing the best methodology or strategy which would possible resolve the problem. Even in the case that the problems have no solution, an understanding why there are not solutions should be gained. This thesis undertook a sequential methodology strategy. However it has to be noted that in almost all research, and in this case, the research is done in rounds. For example, it was planned that first an analysis of relevant literature would be followed by the simulation of the system and the analysis of the model's results; but in the two latter phases, an insight into literature was needed.

The research phases used were:

- **Phase 1 - Literature review:** In the case of electricity markets, there is a great amount of literature available, especially with respect of the liberalization process. This might give a proper quantity of previous research and theories, but as well the great amount

of information can deviate the objective of the researcher. It is true that in order to understand one simple article, most of the times the researcher has to go to the sources which end in other article or book. This dynamic can be infinite, and there need to be a stopping point before the researcher looses the objective of gaining new knowledge.
I strongly suggest researches ask themselves whether the article or book they are about to read, can provide additional and relevant information with respect to the main research question and sub-questions.

- **Phase 2 - Simulation:** This phase is the longest in time and effort. The natural and logical step in simulations is to select a computer program. This is more evident in agent-based, since the system emerges from the interaction of the agents, so no easy-to-solve equations can describe this emergence. Then now, the question is: which program to choose? The Java philosophy (everything can be represented by a class defined by fields and methods) correspond to the agent-based underlying principle of abstracting actors into agents with states and rules and hence seems a good selection. However at the outset, the modeller of this thesis did not have expertises in Java language and so a logic step was to build up the model in Netlogo (simpler programming software in terms of programming effort). Nevertheless, soon it was proven that the calculations needed, especially in the re-dispatching process and thinking of introducing other congestion mechanism, another modelling language was required. For example, if the model used nodal pricing as the congestion mechanism, differential equations would be needed. This could be easily solved by introducing another class into the main Java project, whereas in Netlogo the endeavour would be time consuming and would not add anything relevant to the research's objective. Therefore, to overcome this pitfall, the next option was Repast Symphony, the latest version of the Repast agent-based software tool. Although Repast Simphony enables the use of a more graphical interface, i.e. fluid model component development, the model formalisation was translated into the traditional programming code of classes. This strategy was done because the fluid model component does not give flexibility in the coding side as Java does. Moreover, the codes are clustered into different blocks, this complicates the debug because the modeller loses continuity of the process, for example he has to open and close many times some blocks before finding the error. Hopefully, Repast Symphony allows the use of traditional Java code plus libraries of Repast itself.
I thus, strongly recommend that if the model seems to incorporate a great deal of mathematical computation which Netlogo cannot handle, and if the modeller has patience or previous knowledge of object-oriented languages, use Java to represent the agents in the framework of Repast.

- **Phase 3 - Analysis of results:** It is very difficult to establish upfront which variables will you need to analyze a system, especially in the case where understanding is sought and almost any variable can be the key to a pattern. But if all the variables or a great amount are collect, the analysis may be not straightforward. Therefore, a trade-off needs to be done, between a large amount of data or limited but possible not enough data. The author of this research first took the later of these strategies, but some insight in other variables was needed to understand the results. For example knowing which power plant was in the merit order so as understand the rapid increase of bid position of some power plants. The result was to have in average around 1000000 of variable in one run (20000 ticks times 5 Producers times 5 variables). To cope with this amount of data, the researcher summarized this information by taking average every 100 or 1000 ticks.
I recommend having in mind that Excel macros or other advance statistical programs such as R will be beneficial might be beneficial to analyze a large quantity of data.

- **Phase 4 - Conclusions and Recommendations:** All the work performed should build up arguments which support the final conclusion. However it is a good practise to have an ex-ante idea of the possible conclusion to contrast them with the final conclusion. This could enrich the conclusion by providing surprising results. In simulation works, one cannot rely upon one single run to make a sound conclusion because this simulation presents one possible path of the multiple paths.
  Even more important, is to select the experiments which will be performed. These experiments have to add important and relevant results which help to support a sought conclusion. In the case of this thesis, there are many different experiments which can be selected but, as any other research constrained by time, only the most relevant to the research objective have to chosen. Although, this selection is a not an easy task.
  I recommend to see what experiments have been done in similar research, and to ask for expert insight.

Reflections on the Modeller

At the outset of a research, one of the questions which everybody asks himself or herself is: What topic should I research? This might be the start of a successful or an unsuccessful piece of work. The topic must be amusing for the researcher, to the point that he must be conscious that he might be dealing with the topic for a long period. Therefore, the research should be aligned with his future goals in live, if not will not get a proper attention from the researcher.

Every research has a model, or at least the researcher has a mental model of the system, so the researcher, is as well a modeller. In the case of research which use simulation approaches, the modeller is not only in charge of abstracting the systems into a computer program, but to be aware of the consequences of his or her assumptions and the possible problems he or she may find while modelling. A model, is just a simplification of the world about a particular aspect the researcher is interested in, hence it is wrong and right depending on the perspective.

Agent-based modelling is a relative new simulation paradigm. This fact mostly attracts new researchers who are eager to have a new perspective of a system. But as strategist would note, being a new entrant in the market could attain some risk, especially for the new researcher who do not master a programming language. For example, software tools have not being fully developed to support agent-based analysis, like in the case of System Dynamic (for example: Vensim, Powersim, and so on) or in Discrete Event Simulation (for example: Arena, Goldsim, and so on). Although Repast is one of the principal open source software to undertake an agent-based simulation, its new version Repast Simphony needs further development because it does not give flexibility as it was mentioned before. However, and according to the author of this thesis, Java is a better option but then the modeller has to undertake programming tasks. This implies that the future researcher who wants to use agent-based, might have to understand basis of programming and if possible, have an understanding of an object oriented language.

The use of Java can be beneficial in comparison of Repast Simphony since there is a huge community of users plus there are books and articles which support the learning process. These benefits come at a cost in terms of time invested in learning, especially if the researcher is new in the topic. If the modeller has not previous experience in programming environments, he must take into account that the learning curve at the beginning can be very flat, this means that a lot of effort is needed with relative low progress. However, the reward is invaluable because understanding a programming language such as Java, eases the analysis of problems than hand-calculations could take too much time and effort. Moreover, Java has the great advantage to easily integrate classes developed by others.

An important remark of the modelling and programming phase is that the researcher has to be creative in the sense that some problems that seem to be easy in reality, might be challenging to translate into a machine-readable language.

I suggest to try to represent in as simple as possible logical steps before start programming, i.e. translate the model in algorithms.

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Appendices

Appendices List

Appendix A

Actor Analysis

This appendix gives an overview of the principal actor's interests, perspectives and their position with respect congestion in the European Union.

An Actor analysis gives qualitative insight into the problem. It clarifies the different actors' position with respect to the interests, objectives and means. While an *"interest"* is understood to concern the values and desires that an actor finds *important no matter what the specif* situation is, an *"objective"* belongs to a *specific* problem. Interest can be found by asking questions such as: *Why is the problem situation of importance to an actor? How are actors affected and why do actors care?* Objectives can be revealed by asking question such as: *What does the actor want to achieve when it comes to the problem situation?*

The diference between the desired situation/objective and the existing/expected situation defines the problem according to the actor. In his own view, the actor will identify the cause of the problem and its solution. These actors' views are presented in Table A.1. The actor-specific perspectives define particular objectives which may clash. These perspectives of how the system works, help to identify common ground on actors' position and so understand the tension it may exist.

The dynamic relation amongst the actors and their resources influences the state of the system. The number of producers is not fixed since there is the possibilty of bankruptcy and the assumed low barriers to entry, i.e. the electricity market is assumed to be a contestable market[1]. Since the directives set up the general result without imposing the method, Member States can use, modify and even change the method to manage congestion[2].

[1]For the purpose of this thesis, a fixed amount of producers it is adopted, see Section 5.4

[2]The thesis focuses on the short-term, assuming that the congestion method will be fixed, see Section 5.4

Table A.1: Main actors involved in congestion management in the European Union.

Actors	Interests	Desired situation / objective	Existing / expected situation	Causes	Possible solution
European Commission (EC)	Fair competion and consumer-protection	Low manipulation of electricity price	Manipulation of electricity prices within the EU	Producers' strategic bidding in the case of congestion	Market-based congestion mechanisms
Regulatory Authority	Enforce the EC's legal acts	Low manipulation of electricity price	Manipulation of electricity prices within the country	Congestion mechanism gives space for strategic behaviour	*Change congestion mechanism withing country *Sanctions
Agency	Ensure that the EC's legal acts are applied by Regulatory Authorities and what TSO's are cooperating in the internal market in electricity	Regulation authorities apply congestion mechanism in accordance with Directives	Congestion is caused because the EC guidelines where not applied	Regulatory Authority's decisions are not in compliance with the guidelines	*Recom-mend to RegulatoryAuthorities how to implement guidelines * Assist TSO's in cooperation practies * Inform the EC about guidelines implementation
Transmission System Operator (TSO)	Transport of electricity	Keep the electricity flow within security levels	Higher flow requirements than interconnection capacity	Congestion mechanism gives space for strategic behaviour	Propose changes to directive
Ombudsman	Consumer security	Electricity consumer satisfaction	Electricity consumer dissatisfaction	High electricity tariffs	Investigate consumer's claims
Producers	Profits	Higher electricity price and more sellinf of electricity	Tight congestion management mechanisms	Increase the electricity price	Lobbying

Continued on next page

Continued Main actors involved in congestion management in the European Union.

Actors	Interests	Desired situation / objective	Existing / expected situation	Causes	Possible solution
Small-Scale Consumer	Electricity tariffs	Low as possible electricity price	Higher electricity prices	Liberalization of the electricity sector	Claim to ombudsman
Large-Scale Consumer	Continuity of electricity	Sufficient electricity supply in the case of congestion	Dirsupt production caused by congestion	Liberalization of the electricity sector	Claim to ombudsman
Interconnected Member States (cheap electricity cost)	Public welfare in its own country jurisdiction	Lower or same electricity price	Increase in electricity price	Producers sell electricity to interconnected country	Reduce the interconnection
Interconnected Member States (expensive electricity cost)	Public welfare in its own country jurisdiction	Lower electricity price	Not enough trade in electricity	Limited interconnection capacity	Increase the interconnection

European Commission (EC) Represent the executive body of the European Union. It seeks to uphold the interest of the Union as a whole by drafting new European laws in different policy fields. The policies must protect the whole European Union's inhabitants and businesses, hence it must ensure a competitive atmosphere for businesses while proctection customers. The Directive 2009/72/EC concerning common rules for the internal market and the Regulation (EC) No 714/2009 on conditions for access to the network for cross-border exchanges, are laws that, amongst others things, establish the guidelines to manage congestion so as to strengthen the internal market in electricity. In order to pass the benefits from liberalization to the final customer, the manipulation of the market caused by strategic bidding has to be reduced. The strategy to tackle this issue is to impose marked-based mechanisms. Nevertheless, the guidelines does not restrict the particular method Member States can use (see Section B for an explanation of the market-based mechanisms).

Agency Regarding the Regulation (EC) No 713/2009, an Agency for cooperation among Regulatory Authorities (energy regulators) fills the regulatory gap between Community and Member States. The agency should monitor the cooperation of regional Transmission System Operators in a transparent and efficient way for the benefit of the internal market in electricity and natural gas. The Agency should monitor and analyze the implementation of guidelines in accordance with Regulations. Congestion will therefore occur, if the Regulatory Authorities are not following Regulation and Directives or because TSO's did not properly use the congestion mechanism. Recommendations and opinions regarding regulatory functions, can be sent to the TSO, Regulatory Authorities and to the European Commission.

Regulatory Authority With reference to Article 35(1) of Directive 2009/72/EC, each Member State should designate a single national regulator. The Regulatory Authority along with the Agency, the Member State and the EC, shall cooperate to achieve a competitive, secure and environmentally friendly internal market in electricity. This implies that it should eliminate restrictions on trade in electricity amongst Member States by developing appropriate congestion management methods (that follow the EC guidelines) so as to achieve, in the most cost-effective way, the development of secure, reliable and efficient electricity system. Although Directives provides room to choose a congestion method, it should be based on the market so that the Regulatory Authority can select the congestion method at national level. In the case of congestion, the Regulatory Authority can assess the effictiveness of the congestion method, and in extreme cases, change it so as to decrease the possible manipulation of the electricity price.

Transmission System Operator (TSO) With the liberalization of the electricity sector, the once vertically intergrated undertaking was forced to split into different parts. Of these parts, the TSO is in charge of transporting electricity from the producers to the distribution networks which is in charge of suppling electricity to the final customer. A central facet of the TSO is to develop a feasible schedule of generation using the bids filed by producers and consumers that produced electricity flows which match the capacity of the transmission line, in other words to wheel electricity without congesting the lines. The congestion might take place if producers strategically bid and/or apply trading strategies which artificially creates congestion like in the case of Enron in 2001.

Producers The entities that produce electricity aim to maximize profits. Profits can be increased by either raising the electricity price or the ouput. Although the quantity of output has a maximun level, the electricity price can vary since it follows the principle of supply and demand subjected to physical conditions. The producers perceive the increment of the electricity price, to be rooted to the increase of fuel price. This situation has triggered tougher regulations, leaving less room to get advantages from opportunities to make more profit.

Interconnected Member States The primary interest of governments is to safeguard the interest of their inhabitants within their boundaries. They must ensure that customers enjoy the right to be supplied with electricity of a specific quality at clearly, transparent and reasonable prices. The general authorities hail the interconnection of markets reduces the prices and increase the welfare. However interconnected countries with relatively lower electricity price will experience a price increase, whereas countries with relatively higher electricity prices will note the opposite effect, see Section 2.2. A full interconnection amongst countries, will significally alter the current Member States' electricity price as it will converge towards a common electricity price. This will result in huge opposition and support from Member States depending on the degree of difference between the common and current electricity prices. On one hand, from the standpoint of Members States that have a positive difference, they will be subsidicing the other Member States. On the other hand, Member States with negative differences will benefit from the interconnections, since they can access cheaper-produced electricity.

Large-Scale Consumer This actor refers to costumers which need large amount of electricity, in other words, the industry. The primary aim in to keep producing without interuption. Therefore, they value continuity more than electricity price. In the event of congestion they will be ready to pay more in order to not disrupt its production. The liberalization has affected the investments of the once vertically integrated undertaking, thus increasing the probability of disruption because of congestion. Although this actor does not possess formal power, he can claim to the ombusdman losses in the case of unplanned electricity curtail.

Small-Scale Consumer The customer that purchases electricity for his own consumption has the primary interest in the bill he pays. The bill is the product of his consumption and the assigned tariff. Given that the consumption patterns are difficult to change in order to maintain the same quality of life, the main complaint regards the tariff. Although there are still tariffs that are subsidized by the central government, in the end the customer pays the electricity price (either in the bill or taxes). The liberalization should have caused a decrease in the electricity price, nevertheless this reduction has not been truly seen because of different factors and so eventually the liberalization process is to be blamed. Since this actor does not possess formal power, he can submit his dissatisfaction to the ombusdman by claiming abusive electricity tariffs.

Ombudsman With respect to Article 3(13) of the Directive 2009/72/EC the Member States should secure the creation of an independent body to ensure that complaints are dealt with efficiency. The principal duties of the body is to safeguard consumer security. The dissatisfaction of electricity consumers, who issue claims to the ombudsman, are in generla, rooted in the higher electricity bills. The ombudsman is entitled to perform an investigation and to inform the EC of the results.

With reference to Table A.1 it can be noted that the actors can be clustered into two groups; one which aims to protect the final customers against the possible manipulation of the market by the producers, and another which aims to make profit. Therefore, the former group is regarded to have a *public interest*, whereas the latter has *private interest*.

Taking into account the assumption that the focus in this thesis is the short-term (see Section 5.4), the Ombudsman, the Agency will not be considered since they influence referest to the long-term by providing some feedback to the EC. This feedback can produce a change and adjustments in the system in response to the producers' outcomes.

The interconnected countries' influence on the system is the actual technology used by the producers and will be regarded as part as of the state of the agents. Based on the short-term focus of the system, its influence will not change and will not be considered.

The large-scale consumer and small-scale consumer actors are merged into consumer actor. Although they differ in the principal objective, less outages and cheaper price respectively, they represent the customer who buys and consumes electricity at the end of the value chain (see Figure 5.1).

The *public interest* group tends to view the problem as a consequence of the abuse of the producers who are able to manipulate the final electricity price. It is composed of: the European Commission, the Regulatory Authority, the Transmission Systemem Operator and the Consumer.

The *private interest* group is keen on making profit and hence congestion is seen as an opportunity to increase profits. This group is only composed of the producer.

Appendix B

Available Congestion Management Mechanisms

This Appendix presents the most important congestion mechanisms which Member States could select in order to manage electricity congestion according to the directive drafted by the European Commission.

First the capacity allocation mechanism will be presented, followed by the alleviation mechamisms. Table B.1 presents the two groups of possible congestion mechanisms.

Table B.1: Capacity allocation and alleviation mechanisms

Capacity allocation mechanism		**Capacity alleviation mechanism**
Non-market solutions	* Access limitation * First come, first served * Pro-rata rationing	* Re-dispatching * Counter-trade
Market solutions	* Nodal pricing * Zonal pricing (Market splitting, Market coupling) * Explicit auctioning	

Capacity Allocation Mechanism

The capacity allocation mechanisms aim to assign the physical capacity of the line before the physical delivery of the electricity takes place.

Non-market Solutions

These methods do not give appropriate market signal. The aim is to resolve the congestion by allocating the interconnection capacity to the demanders based on the demanders demand quantity or the chronology of the demand.

Access limitation A few users are allowed to use the interconnection line, discrimination the others users. This method applies in the case of direct current (DC) interconnections with different ownership than the linked network (Kristiansen, 2007a). The gain from the interconnection is limited to the owners of the connection who can influence the price and could act strategically.

First come, first served The method also called in the literature "priority list" refers to the method of allocate the requested capacity submitted by the market players in chronological order. The allocation of the scarce interconnection capacity to the market player will stop when the interconnection capacity has been reached. This method favours incumbents and long-term contracts because these contracts have priority over the recent ones, leaving less or no opportunity for short-term markets (Kristiansen, 2007a). As well the method is sensitive to strategic behaviour since market player might submit bids for higher capacity than they can use knowing the interconnection capacity is limited (Boisseleau and de Vries, 2001). Therefore the players with more recent contract have lower possibility to receive the requested capacity or have a portion of it1 encouraging longer contracts and hampering the success of market dynamic.

Pro-rata rationing If the market players' requested capacity is higher than the interconnection capacity, the mechanism allocates proportional amounts of the capacity they applied for. With respect the "first come, first served mechanism, this method is non discriminatory and more transparent. Nevertheless it also gives room for strategic behaviour because the market player may submit bids for higher capacity in the knowledge that a percentage of it will be allocated. The method basically curtains the market players and do not allocate the scarce interconnection capacity to the player who can pay more for it.

Market Solutions

The European Union Commission showed its preference for market-based method in the Regulation (EC) No 1228/2003, corroborated in the amending presented in 2006 in the article 2.1[1]. The idea is that the market can provide the correct allocation of the interconnection capacity, enhancing the competition among market players and increasing the liquidity of the markets where the capacity is allocated.

Nodal pricing The principal idea of nodal pricing or local marginal pricing, is to (1) model an electricity market with technical and economical conditions, such as power plants capacity, producer's cost function, thermal limits of line connections and so forth (2) optimize the system by maximizing the social welfare (Krause and Andersson, 2006). The nodal pricing approach is based on the theory of spot pricing in electricity markets introduced by Schweppe (1988) and was first proposed by (Hogan, 1992). Proponents have argued that such an approach offers the most efficient allocation of the scarce grid capacity in the short term, as well as sending the correct price signals for producers and consumers in the long run (Rious et al., 2008). Other aspect is the external flows outside of the market due to connection with neighbour electricity markets. This flow deter the results found in the algorithm which basically optimized the network considering the line capacity constraint. This mechanism is used in New York, and New England markets in the USA and in New Zealand (up to 2010) where the market is considerable large.

[1] Article 2.2 states: "Congestion management methods shall be market-based in order to facilitate efficient cross-border trade. For this purpose, capacity shall be allocated only by means of explicit (capacity) or implicit (capacity and energy) auctions. Both methods may coexist on the same interconnection. For intra-day trade continuous trading may be used."

Zonal pricing

- **Market splitting:** In the literature the terms "area price model" and "zonal pricing" (a simplification of nodal pricing) refer to market splitting method. The principle is that injection and withdrawals in different nodes of a network do not have the same impact on the network flows. But it leads to two drawbacks: creation of many illiquid nodal submarkets and enhances unnecessarily the complexity for the market players (Ehrenmann and Smeers, 2005). The logic response to these obstacles is to aggregate the nodes into zones, lowering the number of trades and boosting the trading liquidity. The PX is split into geographical biding areas with limited capacities of exchange; a power pool price is set according to amounts of demand and generation offered in the whole market area. The TSO is in charge of computing the load flows and identifying the congested lines and in every geographical area (formed by one or more bidding areas) a new pool is conceived (ETSO, 2002). One power exchange manages the power flow in its own area. In each geographical area a new pool price is defined; the capacity of the interconnection lines limits the flow among geographical areas. Hence each geographical area has a different pool price: areas downstream of the congestion have a higher pool price, areas upstream of the congestion have a lower pool price. The consumers downstream the congestion pay the highest prices and generators upstream the congestion pay the lower prices. The difference between downstream and upstream price is collected by the system operator.

- **Market coupling:** Is as well a method for integrating electric markets because it depends on at least two electric markets which are connected in the bidding procedure. The objective is to maximize total economic welfare of all the market players; hence, cheaper electricity generation in one country can meet demand and reduce prices in another country. The market players directly benefit from the cross-border exchanges without the need to explicitly acquire the corresponding transmission capacity and increase the efficiency of the interconnection between networks[2]. The difference in the management of flows between the market splitting and market coupling is that the former uses one PX that subdivides the market into regions, whereas the later uses at least two PXs that want to be linked. Therefore market coupling coordinates the use of PXs where different neighbouring regional markets are operating before the congestion in the interconnection takes place. On October 5, 2005, the Nord Pool introduced a market coupling mechanism known as cross-border optimization (CBO) to improve cross-border efficiency between Jutland (West Denmark, DK1) and Germany. The results indicate favourable results with respect of the price transferred to the end customer.

Explicit auctioning: TSO's of the interconnected networks sells interconnection capacity, in an auction process, to the player who value it the most, i.e. the one who offer a higher price. The interconnection capacity is traded among the market players separately from the electricity creating a complexity in the cross-border power trade. In each connecting country, the net transfer capacity (NTC) is assessed and measured so as be separately auctioned in each country or in a joint auction. Commonly, and if there are two countries involved, each TSO's has 50 percentage of the NTC. The bids are considered until all the NTC is completely fulfilled by the bids. The clearing price found from the "transmission marked" is defined by the last considered bid and all the accepted bids are charged with it. This bid can partly be accepted because the NTC has already been met, and the bidder will have a portion of the wanted capacity. The TSO's tend to receive the rents from the auction which can encourage them to create congestion. If there is insufficient unbundling

[2] Retrieved March 2010, from Market Coupling link: http://www.belpex.be/index.php?id=4

the bidder player might be paying to another part of their firm (Boisseleau and de Vries, 2001). This situation can create a distortion in the price, since the firms can bid a high price in order to obtain the capacity without actually paying it since the total cost would be zero (the buyer receives the selling price). Another feature of this method is that it does not necessarily need a power exchange (PX). This reduces potential liquidity for the PX. According to Kristiansen, explicit auction do not ensure flows always going from low energy price to high energy price areas. This was the case in the interconnection between East Denmark and Germany through the Kontek (KT) cable that used the explicit method prior to the coupling one. The difficulty relied on difference of schedules. While the deadline for bidding in EEX was 11:00, in the Nord Pool was at 12:00. Therefore if the expectation in the EEX were incorrect, KT became non-optimal. This difficulty was felt especially on Mondays because the German market is cleared on Friday, while both the Nordic market and the KT auction are cleared on Sunday (Kristiansen, 2007b).

Capacity alleviation mechanism

Also known as remedial methods, these congestion management mechanisms are often used to relieve congestion in real-time (Krause and Andersson, 2006). The aim is to take back the system to secure conditions through the modification of the generation load patterns.

Re-dispatching In this method, the TSO's are in charge of re-dispatching generation and they decide the lowest-priced upward and downward generator. This implies that the TSO's must have the authority to dispatch generator directly. The producers which are re-dispatched are reimbursed for generate electricity and the producers which generation is curtailed are reimburse for avoiding the generation of electricity which might have caused flow higher than thermal limits in the network. The market does not receive any signal of the congestion event nor its solution. Therefore the market players will not act to avoid the congestion since they ignore the event and its solution cost. In the case of Europe, Duthaler (2002) stated:

> [..] an observation made in many zonal markets is that the market schedules transactions that are no longer feasible on the network, since they would breach intra-zonal constraints. The system operator then has to activate real-time redispatch measures, the cost of which is usually socialized.

Counter trade Based on the same principle as re-dispatching, but may be considered market-oriented. Therefore, while in re-dispatching the TSO curtails or increases injections without market-based incentives, in counter trade the process is lead to the market because the TSO enters into a market to buy electricity at prices determined by a bidding process. This method leads to increase trade but it increases the electricity because the TSO must buy at relative higher prices and re-sell the electricity to relative low prices.

Appendix C

Producers' Re-Dispatching Payments

This Appendix detail the profit and payments done to Producers when the congestion mechanism is re-dispatching. It extends the explanation of an re-dispatching example introduced in Section 2.6.

All the Producers are interested in their profits. Profit is equal to revenue minus cost. Revenue is the total amount of electricity produced times the clearing price, and cost is the the money spend on electricity generation.

Basically there are two groups of generators, generators which are within the merit order and generator which are outside the merit order. Note that generators are owned by Producers, and the terminology will be used interchangeable.

- Generators which are withing the merit order and are asked to curtail their electricity production, have to return to the TSO the cost of production which has been avoided.

- Generator which are outside the merit order and are asked to produce electricity get an electricity price higher than the market price.

Generation Plants Within the Merit Order

Producer i

It has the lowest bid of all Producers and hence it is the last generator to be curtailed. The payments are reflected in Figure C.1.

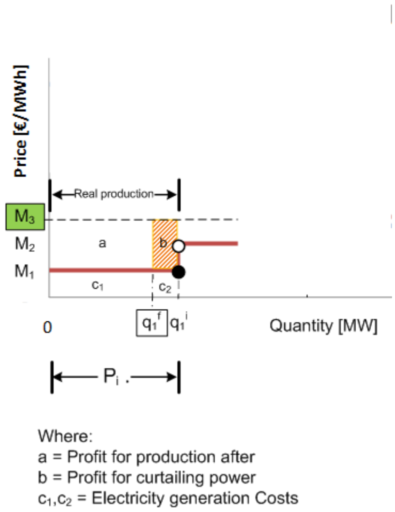

Figure C.1: Payment for Producer i.

- **After the market clearing**
  The Producers P_i should produce its maximum output wich correspond to q_1^i [MWh] and will get an electricity price equal to M_3 [€/MWh]. The profit, revenue and cost are calculated in the Table C.1 which makes reference to Figure C.1.

Table C.1: Profit after market clearing of Producer i.

Variable	Amount [€]	Area
Revenue (R)	$M_3 \cdot q_1^i$	$a + b + c_1 + c_2$
Cost* (C)	$M_1 \cdot q_1^i$	$c_1 + c_2$
Profit (R - C)	$(M_3 - M_1) \cdot q_1^i$	$a + b$

* The TSO assumes that the bid reflects the Producer's cost posistion. However this bid can be different from the generation cost.

- **After the congestion clearing**
  The TSO curtailed the capacity of the Producers P_i up to the quantity q_1^f [MWh]. So the reduced capacity is $(q_1^i - q_1^f)$ [MWh]. Producer i has to reimburse the cost avoided to generate electricity. These results are presented in Table C.2.

Table C.2: Profit after congestion clearing of Producer i.

Variable	Amount [€]	Area
Revenue (R)	$M_3 \cdot q_1^i$	$a + b + c_1 + c_2$
Reimburse to TSO (Re)	$M_1 \cdot q_1^f$	c_1
Net Revenue (NR=R-Re)	$M_3 \cdot q_1^i - M_1 \cdot q_1^f$	$a + b + c_2$
Cost of production* (C)	$(q_1^f - q_1^i) \cdot M_1$	c_2
Net Profit after clearing congestion (P-Re)	$(M_3 - M_t) \cdot q_1^i$	$a + b$

* The TSO assumes that the bid reflects the Producer's cost posistion. However this bid can be different from the generation cost.

Producer j

It has the second lowest bid of all Producers. Given that the system ..... The payments are reflected in Figure C.2.

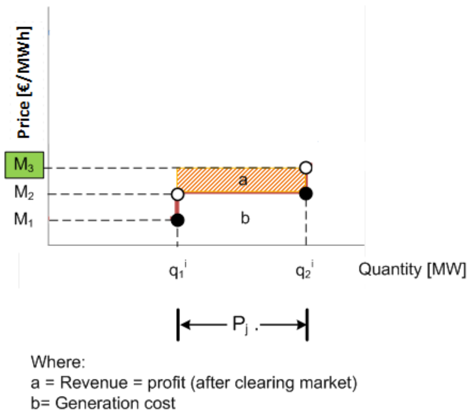

Figure C.2: Payments for Producer j.

- **After the market clearing**
  The Producers P_j should produce its maximum output wich correspond to $(q_2^i - q_1^i)$ [MWh] and will get an electricity price equal to M_3 [€/MWh]. The profit, revenue and cost are calculated in the Table C.3 which makes reference to Figure C.2.

Table C.3: Profit after market clearing of Producer i.

Variable	Amount [€]	Area
Revenue (R)	$M_3 \cdot (q_2^i - q_1^i)$	$a + b$
Cost* (C)	$M_2 \cdot (q_2^i - q_1^i)$	b
Profit (R - C)	$(M_3 - M_2) \cdot (q_2^i - q_1^i)$	a

* The TSO assumes that the bid reflects the Producer's cost posistion. However this bid can be different from the generation cost.

- **After the congestion clearing**
  The TSO curtailed all the capacity of the Producers P_j. Thus Producer P_j has to reimburse the cost of generation which was avoided. However it will still receive a payment without producing any electricity. The calculations are presented in Table C.4.

Table C.4: Profit after congestion clearing of Producer j.

Variable	Amount [€]	Area
Revenue (R)	$M_3 \cdot (q_2^i - q_1^i)$	$a+b$
Reimburse to TSO (Re)	$M_2 \cdot (q_2^i - q_1^i)$	b
Net Revenue (NR=R-Re)	$(M_3 - M_2) \cdot (q_2^i - q_1^i)$	a
Cost of production* (C)	0	-
Net Profit after clearing congestion (P-Re)	$(M_3 - M_2) \cdot (q_2^i - q_1^i)$	a

* The TSO assumes that the bid reflects the Producer's cost posistion. However this bid can be different from the generation cost.

Producer k

It has the second lowest bid of all Producers. Given that the system ..... The payments are reflected in Figure C.3.

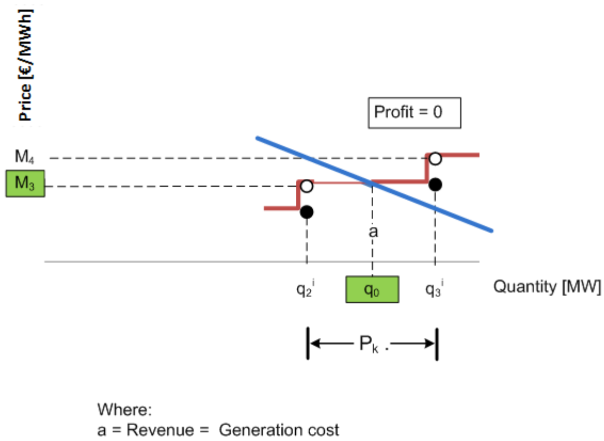

Figure C.3: Payment for Producer k.

- **After the market clearing**
  The Producers P_k produces $(q_0 - q_2^i)$ [MWh] which is less than its maximum output. It will get an electricity price equal to M_3 [€/MWh] which is its original bid, hence P_k is the marginal unit. The profit, revenue and cost are calculated in the Table C.5 which makes reference to Figure C.2.

Table C.5: Profit after market clearing of Producer k.

Variable	Amount [€]	Area
Revenue (R)	$M_3 \cdot (q_2^i - q_0)$	a
Cost* (C)	$M_3 \cdot (q_2^i - q_0)$	a
Profit (R - C)	0	-

* The TSO assumes that the bid reflects the Producer's cost posistion. However this bid can be different from the generation cost.

- **After the congestion clearing**
  The TSO curtailed all the capacity of the Producers P_j. Thus Producer P_j has to reimburse the cost of generation which was avoided. However it will still receive a payment without producing any electricity. The calculations are presented in Table C.6.

Table C.6: Profit after congestion clearing of Producer k.

Variable	Amount [€]	Area
Revenue (R)	$M_3 \cdot (q_0 - q_2^i)$	a
Reimburse to TSO (Re)	$M_3 \cdot (q_0 - q_2^i)$	a
Net Revenue (NR=R-Re)	0	-
Cost of production* (C)	0	-
Net Profit after clearing congestion (P-Re)	0	-

* The TSO assumes that the bid reflects the Producer's cost posistion. However this bid can be different from the generation cost.

Generation Plants Outside the Merit Order

Producer l

It has the next highest bid after the marginal generator, hence it is out of the merit order. The payments are depicted in Figure C.4.

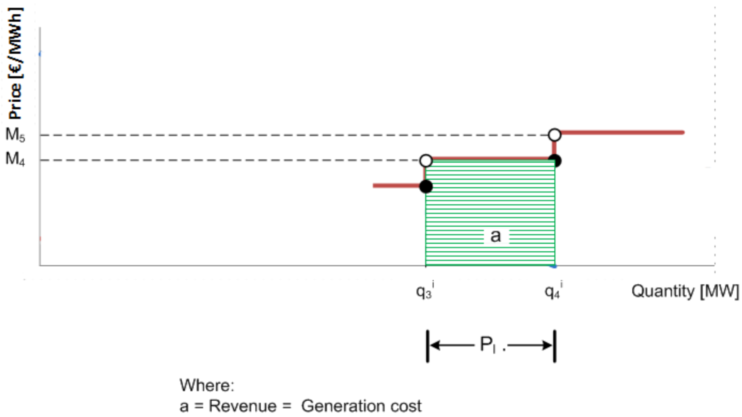

Figure C.4: Payment for Producer l.

- **After the market clearing**
  The Producers P_l does not produce any amount of electricity, so its revenue, cost and profit are all 0 as Table C.7 points out.

- **After the congestion clearing**
  The TSO has to replace the electricity he curtailed from producers P_i ,P_j and P_k. First it will re-dispatch P_l because it has the cheapest cost amongst the producers outside the

Table C.7: Profit after market clearing of Producer l.

Variable	Amount [€]	Area
Revenue (R)	0	-
Cost (C)	0	-
Profit (R - C)	0	-

Table C.8: Profit after congestion clearing of Producer l.

Variable	Amount [€]	Area
Revenue (R)	$(q_4^i - q_3^i) \cdot M_4$	a
Cost of production (C)	$(q_4^i - q_3^i) \cdot M_4$	a
Net Profit after clearing congestion (R-C)	0	$-$

merit order. The TSO pays the electricity produced by P_l at the Producer bid M_4 because this represents its willingness in terms of money to generate electricity. Note that M_4 is higher than the market clearing price M_3. This calculations are presented in Table C.8.

Appendix D

Simulation Paradigms Description

This appendix describes the main simulation paradigms suitable to analyze the *European Wholesale Electricity Market* as indicated in Section 3.3.

A simulation paradigm has its own characteristics and application arena. Based on the objective of the study and the system, the degree of abstraction to model the system can be defined. According to the degree of abstraction, Figure D.1 presents and overview of the main simulation paradigms.

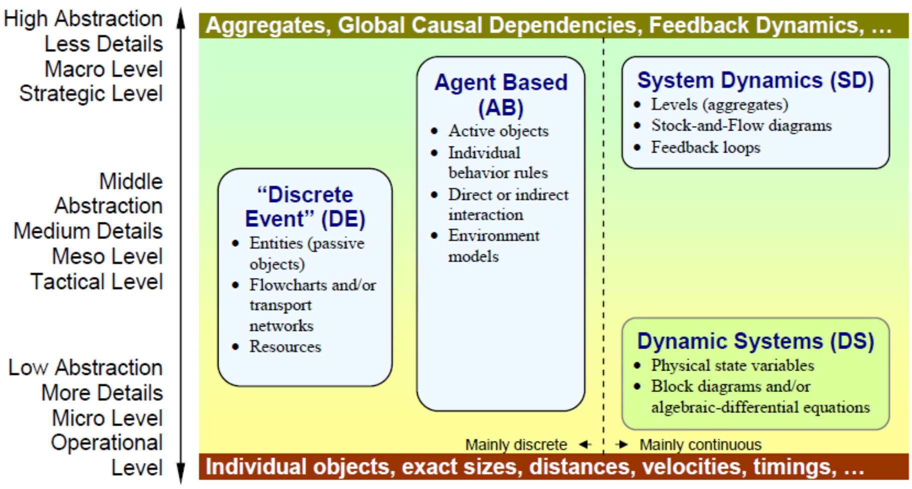

Figure D.1: Modelling approaches Borshchev and Filippov (2004).

System dynamics SD Undertakes a top-down approach with the use of differential equations. This means that SD aggregates entities, thus entities should be homogenous in principle. The objective of SD is to clarify relations between the behaviour of a system as a function of time and its underlying structure (Wolstenholme, 1989). Feedback play an important role in system dynamics, and the main assumption is that the behaviour of a system is principally caused by the structure of the system (Erick et al., 2008). SD is holistic and hence quote such as "everything is connected to everything else" generally appear in SD jargon like Sterman (2001) mentined. This implies that in SD there are global structural dependencies and SD concerns with the systems and all system dimensions, not with their parts/dimensions (Erick et al., 2008).

Dynamic systems DS Mathematically, DS consist of differential equations but the integrated variables are not aggregates of any entities (like in the case of SD) and have a physical meaning such as position, velocity, concentration, and so forth (Borshchev and Filippov, 2004). Thus DS are generally applicable on physical systems. For example control of velocity in automated vehicles. Like in the case of SD, DS assumes a static structure because the differential equation, which both approaches are based on, defines the underlying system structure.

Discrete-event modelling DE Combines a bottom-up a top-down approach. It is generally used to develop an understanding of the performance of a complicated system over time. DE consists of working through a list of events, all taking place at a specific time (Verbraeck et al., 2005). For example, understand how the number of operators working at a phone bank affects the percent of callers getting a busy signal. In DE the entities are passive objects and the rules that steer the systeme are concentrated in the flowchart blocks (Borshchev and Filippov, 2004).

Agent-based modelling AB Assumes a bottom-up approach which models the behaviour of the constituent parts (agents) rather than the results of their actions (van Dam and Chappin, 2010). AB is decentralized, this means the global system behaviour (dynamics) is not explicitly defined (Borshchev and Filippov, 2004). Actually the agents' states and rules are coded and the global behaviour emerges as a result of the interaction of the agents which follow their own rules or behaviour, living together in some environment and communicating with each other and with the environment. For example the flock of birds can be simulated with agents who represent birds following three rules[1]: "alignment", "separation", and "cohesion".

[1] Further detail of the model at http://www.red3d.com/cwr/boids/

Appendix E

Neoclassical Profit Maximization

This Appendix illustrates the procedure to find the theoretical equilibrium in case of monopolistic competion, doupoly (Cournot Case) and in perfect competition.

Monopolistic Case

There is only 1 Producers, 1 TSO and Consumers. For calculation and illustration purposes, it was assumed a less stepper demand curve.

Demand Curve: $P = 40 - 0.2X$ where X is quantity and P is price.

Cost function: $TC = 15 + 10X$ where X is quantity.

This means that the monopolist has a fixed cost equatl to 15 [€/MW] and a variable cost of 10 [€/MWh].

Profit (Π) is equal to revenue (R) minus cost (C). The revenue is quantity (X) times prices (P). The Cost depends upon the quantity (X) produced and is expressed in average cost (AC) times the quantity (X). Thus:

$\Pi = R - C = (P)(X) - (AC)(X)$ where $AC = \frac{TC}{X} = \frac{15}{X} + 10$

Given that the monopolistic is profit seeker, it will try to maximize its profit, so:

$\frac{\partial \Pi}{\partial X} = 0 \Rightarrow \frac{\partial}{\partial X}(R - C) = MR - MC = 0 \Rightarrow MR = MC$ Where MR is the marginal revenue and MC is the marginal cost.

Now:

$MR = \frac{\partial R}{\partial X} = \frac{\partial}{\partial X}((P)(X)) = \frac{\partial P}{\partial X}X + P$

the quantity (P) is found from the demand curve, so

$MR = -0.2X + 40 - 0.2X \Rightarrow MR = 40 - 0.4X$

and

$MC = \frac{\partial C}{\partial X} = \frac{\partial}{\partial X}((AC)(X)) = \frac{\partial}{\partial X}(15 + 10X) = 10$

Since $MR = MC$ then $40 - 0.4X = 10 \Rightarrow X = \frac{30}{0.4} \Rightarrow X = 75$ replacing into the demand curve, we obtain $P = 25$

To sum up, in order to maximize profits, the monopolistic Producer should offer 75 [MW] at 25 [€/MWh].

Doupoly - Cournot Case

There are 2 Producers, 1 TSO and Consumers. For calculation and illustration purposes, it was assumed a less stepper demand curve (as in the monopolitic case).

Demand Curve: $P = 40 - 0.2X$ where $X = X_1 + X_2$ is total quantity and P is price.

Cost function (Producer1): $TC_1 = 15 + 10X_1$ where X_1 is quantity of Producer 1.

Cost function (Producer2): $TC_2 = 15 + 10X_2$ where X_2 is quantity of Producer 2.

This means that both Producers have a fixed cost equatl to 15 [€/MW] and a variable cost of 10 [€/MWh].

Profit (Π) is equal to revenue (R) minus cost (C). The revenue is quantity (X) times prices (P). The Cost depends upon the quantity of each producer (X) produced and is expressed in average cost (AC) times the quantity (X). Thus:

$\Pi_1 = R_1 - C_1 = (P)(X_1) - (AC)(X_1)$ where $AC = \frac{TC}{X_1} = \frac{15}{X_1} + 10$

and

$\Pi_2 = R_2 - C_2 = (P)(X_2) - (AC)(X_2)$ where $AC = \frac{TC}{X_2} = \frac{15}{X_2} + 10$

Given that both Producers are profit seeker, they will try to maximize their profit, so:

$\frac{\partial \Pi_i}{\partial X_i} = 0 \Rightarrow \frac{\partial}{\partial X_i}(R_i - C_i) = MR_i - MC = 0 \Rightarrow MR_i = MC$ Where MR_i is the marginal revenue for Producer $i \in \{1, 2\}$ and MC is the marginal cost (equal to both Producers).

Now:

$MR_i = \frac{\partial R_i}{\partial X_i} = \frac{\partial}{\partial X_i}((P)(X_i)) = \frac{\partial P}{\partial X_i} X_i + P$ where $i \in \{1, 2\}$

the quantity (P) is found from the demand curve, so

$MR_1 = -0.2X_1 + 40 - 0.2(X_1 + X_2) \Rightarrow MR_1 = 40 - 0.4X_1 - 0.2X_2$

conversely

$MR_2 = -0.2X_2 + 40 - 0.2(X_1 + X_2) \Rightarrow MR_2 = 40 - 0.4X_2 - 0.2X_1$

and

$MC = \frac{\partial C}{\partial X} = \frac{\partial}{\partial X}((AC)(X)) = \frac{\partial}{\partial X}(15 + 10X) = 10$

Since $MR_i = MC$ where $i \in \{1, 2\}$, then

$40 - 0.4X_1 - 0.2X_2 = 10$

and

$40 - 0.4X_2 - 0.2X_1 = 10$

which forms a sytem of 2 equations and 2 variables:

$\left\{ \begin{matrix} 30 = 0.4X_1 + 0.2X_2 \\ 30 = 0.2X_1 + 0.4X_2 \end{matrix} \right\}$

Which results in: $X_1 = X_2 = 50 \Rightarrow X = 100$ replacing into the demand curve, we obtain $P = 20$

To sum up, in order to maximize profits, Producers should offer 50 [MW] at 20 [€/MWh].

Perfect Competition

In a perfect competitive market, Producers cannot alter the price of the electricity, i.e. they are price taker.

There are 3 Producers with:

Cost function (Producer i): $TC_i = 15 + 10X_i$ where X_i is quantity of Producer $i \in \{1, .., 3\}$.

Profit of (Π_i) is equal to revenue (R) minus cost (C). The revenue is quantity (X) times prices (P). The Cost depends upon the quantity (X) produced and is expressed in average cost (AC) times the quantity (X). Thus for a Producer i:

$\Pi_i = R_i - C_i = (P)(X_i) - (AC_i)(X_i)$ where $AC = \frac{TC}{X} = \frac{15}{X} + 10$

Given that all Producers are profit seeker, each one of the producers will try to maximize its profit, so:

$\frac{\partial \Pi_i}{\partial X_i} = 0 \Rightarrow \frac{\partial}{\partial X_i}(R_i - C_i) = MR_i - MC_i = 0 \Rightarrow MR_i = MC_i$ Where MR_i is the marginal revenue and MCi is the marginal cost of Producer $i \in \{1,..,3\}$.

Now:

$MR_i = \frac{\partial R_i}{\partial X_i} = \frac{\partial}{\partial X_i}((P)(X_i)) = \frac{\partial P}{\partial X_i} X_i + P$ where $i \in \{1,..,3\}$

However, by assumption of perfect competitive markets, $\frac{\partial P}{\partial X_i} = 0$ so $MR_i = P$

On the other hand we have $MC_i = \frac{\partial C_i}{\partial X_i} = \frac{\partial}{\partial X_i}((AC_i)(X_i)) = \frac{\partial}{\partial X_i}(15 + 10X_i) = 10$

Therefore, $MR_i = MC_i \Longrightarrow P = 10$

In conclusion, in perfect competitive markets, all the Producers offer 50 [MW] at 10 [€/MWh].

Appendix F

Market Clearing Process

In this Appendix, two cases which can be found in the clearing process are presented.

In general, in electricity markets the market clearing process is done using the unique auction methodology. The methodology establishes a unique price for all producers which match with the demand curve. There are two cases where demand and supply match. In the case that the demand curve intersected the supply curve within the production range of a producer and so the clearing price will be the producer bidding price and the quantity will be the aggregated supply value, see Figure F.1.

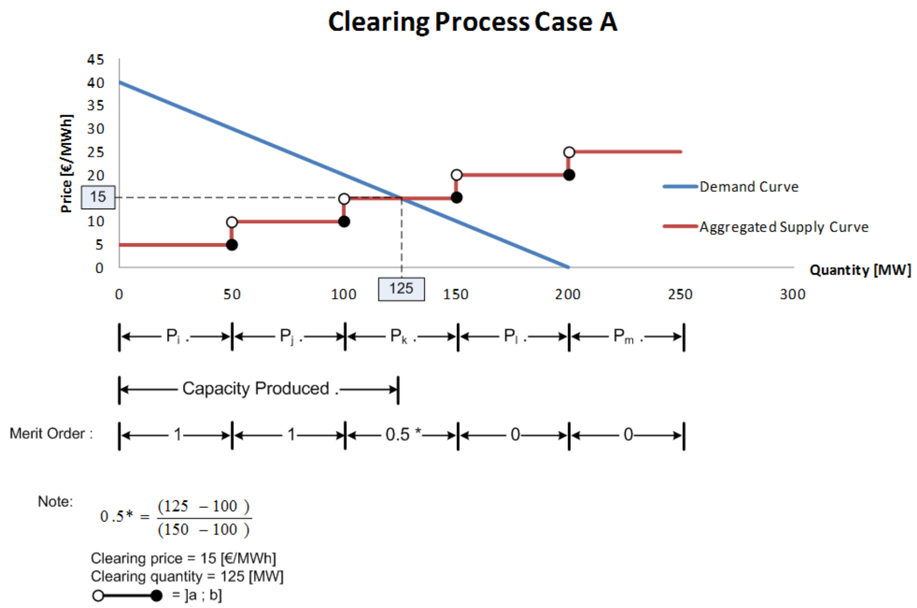

Figure F.1: Clearing process case A.

In the case that the demand intersected the vertical line which connects two suppliers, the quantity watches with the last producer in the merit order, but the price is higher than the producer bid price, see Figure F.2.

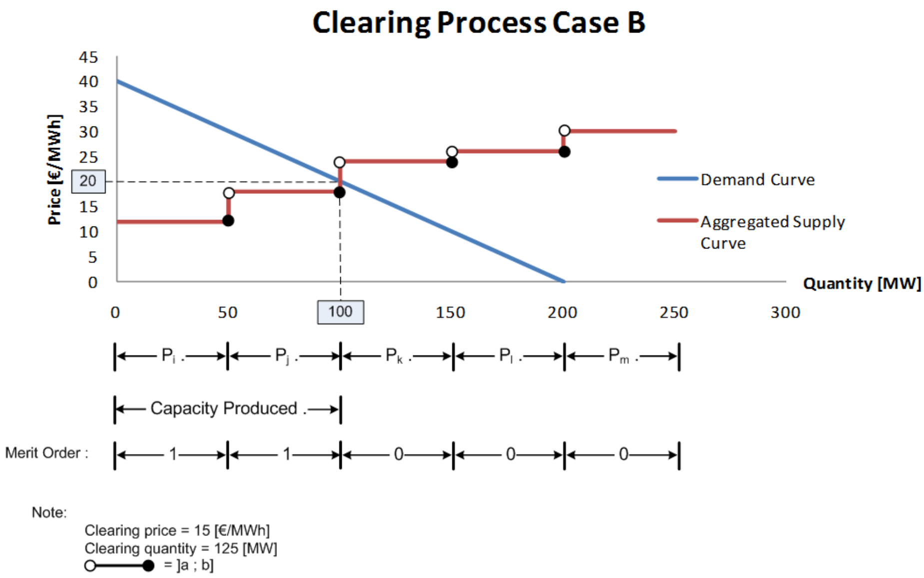

Figure F.2: Clearing process case B.

Appendix G

Agents Workflow and Class Diagram

This Appendix details the work flow which agents underke in every tick and the correspondant class diagram.

Agents Workflow

The Figure G.1 presents the workflow that agents undertake in each tick. The sequence of activies is:

> The *Transmission System Operator* simultaneously demands the electricity demand and the bid's position to the *Consumers* and *Producers* respectively. While the *Consumers* calculate their demand, the *Producers* establish their positions as follows: (1) the present power plant capacity and its marginal costs is determined, (2) second the strategy based on the previous information and the benefits from the previous tick, will determine the block of electricity and respective price, in other words the bid's position of each *Producer*. Once the *Consumers*' demand and *Producers*' bid are available, the *Transmission System Operator* will clear the market by applying the market clearing algorithm. This process will give as result the flows in the network. If the flow of any line is higher than the line capacity, there exist congestion and therefore a congestion mechanism must be applied. In the event in which no line is congested, or after clearing any congestion, the *Transmission System Operator* will communicate the merit order and the electricity price. The *Producers* which are included in the merit order will thus produce the electricity to meet the *Customer*'s demand. On the basis of the electricity price and the cost of production, each *Producer* calculates its benefit. This benefit will influence the strategy in the next tick.

The activities undertaken by the agents must give as result the flow of electricity within security limits generated with the cheapest power plants.

Class Diagram

As explained in Section 6.4 the market is composed of 3 participants, Consumers, the Transmissino System Operator and Producers. Figure G.2 depicts the class diagram of the agent which represent the attributes (states) and methods (rules). Note that attibutes and methods have the caracteristic of being private (-) or public (+). For example the producers position is a private information that the Transmission System Operator do not share with other Producers.

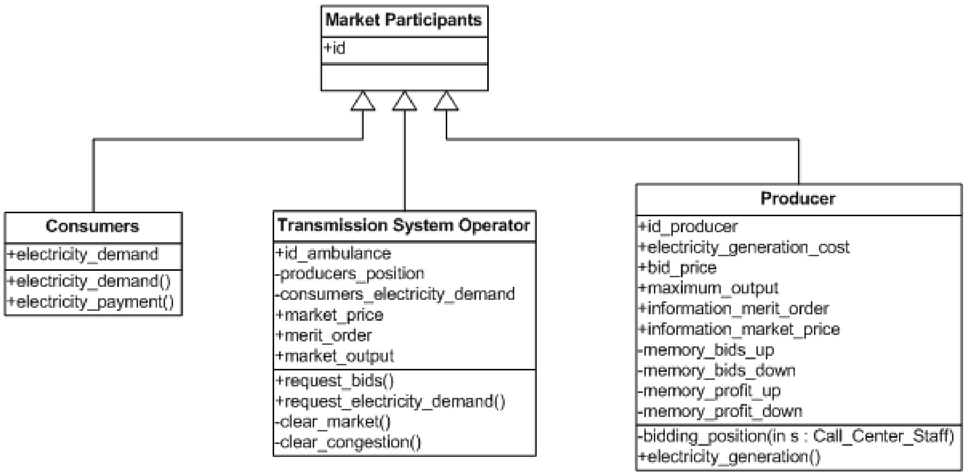

Figure G.2: Class diagram.

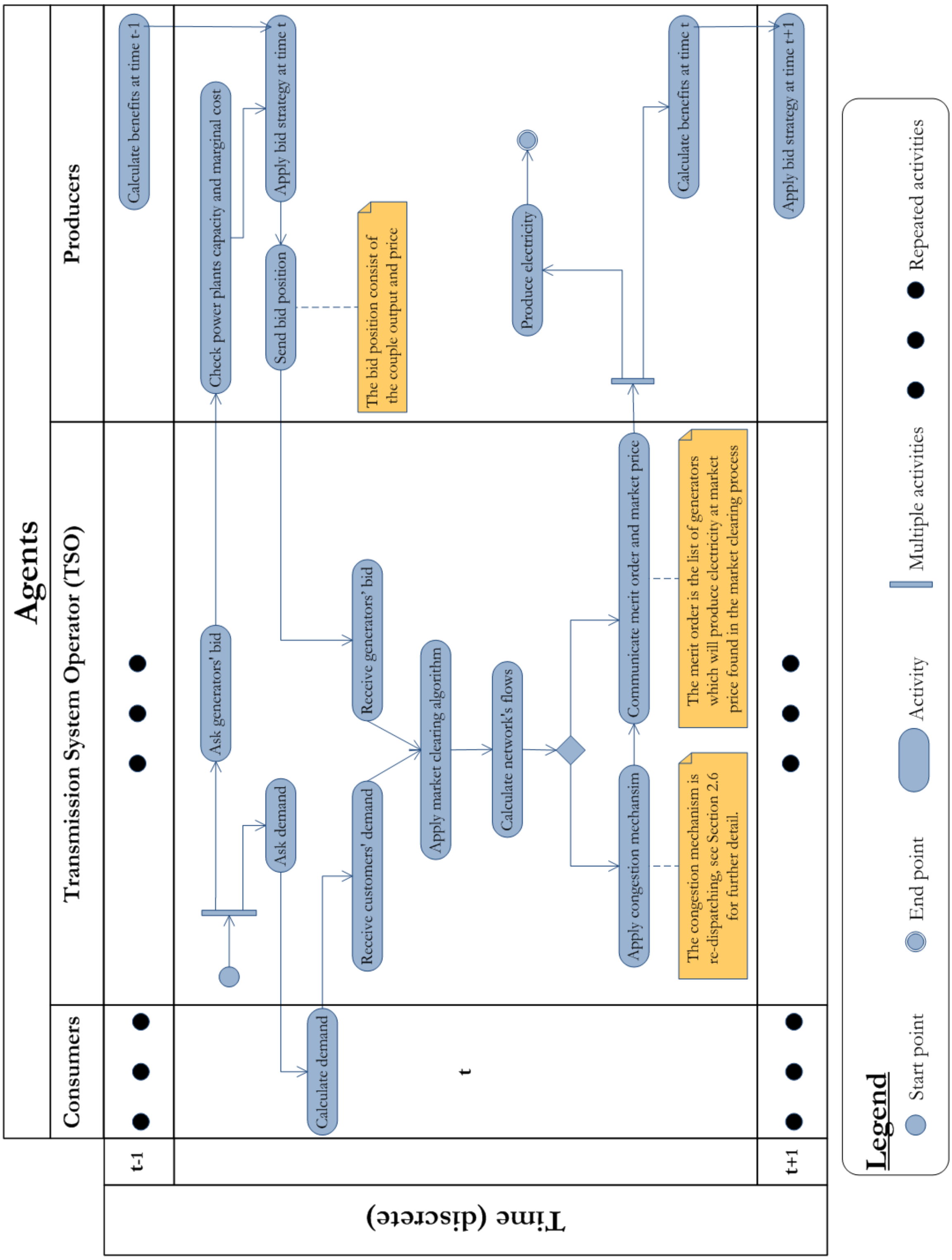

Figure G.1: Agents workflow.

Appendix H

CD with Repast Model

A CD with the models developed are attached below. The models are introduced into 3 different files, namely Monopolistic Case, Duopoly Case and Complete Case. The Monopolistic Case present the model with 1 Producer, 1 TSO and the Consumers. The Duopoly Case has 2 Producers, 1 TSO and Consumers. The Complete Case presents all the Producers (3 Producers and 5 generation plants), 1 TSO and the Consumers.

The cases are written in Repast Simphony, therefore to be run, they need to be imported into the Repast Simphony interface.