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DEPARTMENT. ELEKTROTECHNIEK (ESAT)
AFDELING ELEKTRISCHE ENERGIE EN
COMPUTERARCHITECTUREN (ELECTA)
Kasteelpark Arenberg 10 - 3001 Leuven (Heverlee)

POWER EXCHANGE
AUCTION TRADING PLATFORM DESIGN

Promotoren:

Prof. Dr. ir. habil. R. BELMANS
Prof. Dr. S. PROOST

Proefschrift voorgedragen tot
het behalen van het doctoraat
in de toegepaste wetenschappen

door

Leonardo Meeus

July 2006

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Preface

In the final year of my master studies handelsingenieur at the department of applied economics, it was the first time that Prof W. D'haeseleer (mechanical engineering), Prof R. Belmans (electrical engineering) and Prof S. Proost (economics) taught the different perspectives their disciplines have on energy. When Prof Belmans sent an email to ask whether somebody was interested in doing multidisciplinary research for his research group, I knew that this was the challenge I was looking for.

It has been a great pleasure to work for Ronnie. Partly due to his omni presence in industry, he non-stop provides interesting research challenges. Perhaps the most important lesson he taught me is to take full advantage of win-win opportunities in dealing with these challenges. I enjoyed working with Konrad, Dirk, Thomas, Karolien, Leen and Stijn on diverse projects. Special thanks also to office mates Tom and Konrad with whom I took my first steps in the electrical engineering department. With the entry of Karolien and later also Leen, our office has become an oases of handelsingenieurs inside the department. They, together with all colleagues at ELECTA, make it a pleasant place to work.

Thanks to Ronnie, I also became acquainted with power exchanges, doing project work for the APX Group and soon after also for Elia and Belpex. These projects have motivated me intensely and I enjoyed very much the discussions with all people involved. They are too many to mention, but not specifically thanking Paul Boonekamp, Philippe Chevalier, Andrew Claxton, Bert den Ouden, Philippe Halain, Tsjerk Tack, Frank Van den Berghe, and Frank Vermeulen would be very ungrateful.

Despite my initial intentions, I was easily convinced to work towards a PhD on the same topic. Prof Proost kindly accepted to be my co-promoter. Stef and his collaborators Bert and Guido have helped maturing my ideas and also had a great influence on the finalization of this text. I wish my proofreaders Erik, Hans, Karolien, Leen and Paula all the best with their own papers and thesis.

By founding the European Energy Institute, William and Ronnie have recently intensified multi-disciplinary research in energy across national borders. I personally benefited from this initiative by working with Paris XI. Many thanks to Prof J. M. Glachant and Marcelo Saguan for an amicable collaboration. Thanks also to Yannick Perez to give me the opportunity to present my PhD in Paris in preparation of my final presentation.

I have been fortunate interacting with many inspiring people of many disciplines, industries and countries, with whom I hope to continue working in the future. Still, my devotion goes to my Italian connection and partner in love Francesca. She, in close collaboration with friends and family, makes my life complete.

Leonardo Meeus
Nijlen, July 2006

Abstract

This study analyzes the auctions organized by power exchanges in Europe. Power exchanges are institutions that facilitate wholesale trade in electric energy. Most exchanges organize separate auctions day ahead for every hour of the next day. Generators, large consumers, suppliers and traders fine-tune their portfolios via these trading platforms.

Most exchanges originally only organized trade within national borders. Increasingly, they are also involved in facilitating cross-border trade. The changing context implies new challenges but also renews the discussion on how former challenges have been addressed.

This work provides insight into the problems faced by exchanges. The auction problem is modeled as a constrained optimization problem and alternative solutions are analyzed. In its role of auctioneer, the exchange receives orders introduced by market parties and then decides which to accept and at which prices to settle the contracts. Taking this decision is not straightforward due to network constraints, order formats (block orders), and political constraints. The text is divided in three parts, respectively addressing these issues.

Samenvatting

Deze studie analyseert de door elektrische energiebeurzen georganiseerde veilingen in Europa. Beurzen zijn instituties die de groothandel in elektrische energie vergemakkelijken. De meeste beurzen organiseren aparte veilingen een dag voordat de levering plaatsvindt voor elk uur van de volgende dag. Generatoren, grootverbruikers, leveranciers en handelaars optimaliseren hun portfolio's via deze handelsplatformen.

Initieel organiseerden de meeste beurzen in Europa handel binnen nationale grenzen. In toenemende mate worden ze ook betrokken bij het organiseren van grensoverschrijdende handel. De veranderende context impliceert nieuwe uitdagingen maar hernieuwt ook de discussie over hoe vroegere uitdagingen werden aangepakt.

Dit werk geeft inzicht in de problemen waarmee beurzen te kampen hebben. Het veilingsysteem is gemodelleerd als een optimalisatieprobleem met beperkingen en alternatieve oplossingen worden onderzocht. In zijn rol als veilingmeester, ontvangt de beurs door marktpartijen geïntroduceerde orders en beslist dan welke orders te aanvaarden en aan welke prijzen de contracten worden afgerekend. Het nemen van deze beslissing is niet vanzelfsprekend door netwerkbeperkingen, order formaten (blokorders) en politieke beperkingen. De tekst is onderverdeeld in drie delen die respectievelijk deze thema's bespreken.

Table of Contents

Nederlandstalige samenvatting

I. Ontwerp van een veilingsysteem voor elektrische energiebeurzen

De liberalisering van de elektriciteitsindustrie in de Europese Unie ging van start met de invoering van Richtlijn 96/92/EC en werd later versneld met Richtlijn 2003/54/EC. De vrijmaking kadert in de creatie van een Interne Markt met vrij verkeer van mensen, kapitaal en goederen zoals vastgelegd in de Europese Verdragen. Er wordt een verbeterde competitiviteit van de industrie nagestreefd met de introductie van concurrentie in de opwekking en levering van elektrische energie. Netwerkactiviteiten worden beschouwd als een natuurlijk monopolie en zijn daarom gereguleerd.

Elektrische energie is een secundaire energiedrager die men verkrijgt door de omzetting van primaire brandstoffen zoals steenkool, olie, aardgas en uranium, maar in toenemende mate ook uit hernieuwbare bronnen zoals de reeds lang gebruikte waterkracht en windenergie. Elektrische energie kan daarenboven economisch niet in grote hoeveelheden en niet voor lange duur worden opgeslagen. Daarom moet op elk ogenblik de belasting van het netwerk gelijk zijn aan wat er in het netwerk wordt geïnjecteerd door de verschillende generatoren die met het netwerk verbonden zijn.

De netwerkgebruikers of hun vertegenwoordigers staan in voor het individueel evenwicht per evenwichtsperiode. Dat wil zeggen dat producenten per evenwichtsperiode zo goed mogelijk hun productie overeen laten komen met wat ze gecontracteerd hebben en dat grootverbruikers en leveranciers in de groothandelmarkt zo goed mogelijk aankopen wat ze denken te verbruiken. Onbalans wordt ontmoedigd met boetes die gebaseerd zijn op de kost van het regel– en reserve vermogen dat de netwerkbeheerder aankoopt bij de netwerkgebruikers om de globale onbalans op te heffen. Elk land heeft ten minste één zone waarin een netwerkbeheerder instaat voor het globale evenwicht.

Op groothandel niveau kan elektrische energie vele malen verhandeld worden alvorens de uiteindelijke levering plaatsvindt. Dit gebeurt aan prijzen die sterk kunnen schommelen naarmate de verwachtingen omtrent productie en verbruik zich aanpassen in functie van de beschikbare informatie. Hoe dichter bij het moment van levering, des te kleiner en meer specifiek de noden zijn enerzijds, en des te moeilijker het wordt nog een tegenpartij te vinden anderzijds. Beurzen spelen in op dit probleem door geautomatiseerde handelsplatformen aan te bieden waar anoniem en volgens vereenvoudigde regels gehandeld kan worden met garantie van betaling.

Beurzen zijn het meest bekend voor hun veilingsystemen waarin gestandaardiseerde uurcontracten worden verhandeld één dag voor de uiteindelijke levering. De uurprijzen die zij publiceren zijn een belangrijke referentie voor handel in andere markten. In toenemende mate worden er ook financiële producten ontwikkeld die deze prijzen gebruiken als referentieprijs. Meer en meer organiseren de beurzen via hun veilingsystemen ook de grensoverschrijdende handel in samenwerking met de netwerkbeheerders en hierdoor winnen zij aan belang.

Het is in deze context dat onderzoek naar de ontwikkeling van een veilingsysteem voor stroombeurzen werd verricht. De rol van beurzen in de creatie van een Interne Elektriciteitsmarkt in Europa is reeds besproken door anderen, zodat dit doctoraatswerk zich concentreert op de implementatie en functionering van het veilingsysteem.

In essentie moet de beurs op basis van ontvangen orders voor verschillende uren, eventueel van verschillende locaties, beslissen wie handelt en aan welke prijzen. De beurs laat zich bij die beslissing leiden door een zo min mogelijk betwistbaar objectief, zoals maximale totale handelswinst voor haar participanten. Met andere woorden, een veilingsysteem kan gemodelleerd worden als een optimalisatieprobleem met beperkingen, zodat bestaande commerciële software kan gebruikt worden om het op te lossen.

De uitdagingen voor een beurs hebben betrekking tot het omgaan met netwerkbeperkingen, order formaten (blokorders) en politieke beperkingen. De drie delen van deze tekst behandelen respectievelijk deze drie uitdagingen. In deze Nederlandstalige samenvatting wordt echter enkel ingegaan op de kern van het doctoraat: de behandeling van blokorders (hoofdstuk 5-8). Alvorens de voornaamste bijdragen samen te vatten, volgt er een korte inleidende beschouwing over het belang van een beurs in de markt.

II. Belang van elektrische energiebeurzen in Europa

De elektriciteitsindustrie is vanouds gekenmerkt door verticale integratie en regulering. Bovendien zijn de nationale transmissienetwerken verbonden om mekaar te kunnen bijstaan in geval van nood, maar niet om de ruggengraat te vormen van een Interne Elektriciteitsmarkt in Europa. Het is dus allesbehalve vanzelfsprekend om over te gaan naar een marktsysteem in deze sector. Het ontwerp van een systeem dat marktwerking mogelijk maakt, is daarom van cruciaal belang voor de competitiviteit van de elektriciteitsindustrie en dus ook voor de competitiviteit van de Europese economie in zijn geheel.

Merk op dat een elektriciteitsmarkt niet staat of valt met de implementatie van een beurs. Een beurs is slechts een onderdeel van het marktsysteem en misschien niet eens strikt noodzakelijk. Een beurs creëert geen concurrentie waar de marktstructuur het niet toelaat. Een beurs bevordert enkel de handel door bepaalde diensten aan te bieden via een handelsplatform en kan zo transactiekosten helpen verminderen en handel stimuleren. Anderzijds is een goedwerkende beurs wel een indicatie van een meer volwassen markt.

Deelname aan de beurzen in Europa is vrijblijvend. Hierin verschillen de Europese groothandelsmarkten fundamenteel van bijvoorbeeld de Amerikaanse. Op veel andere plaatsen in de wereld vindt groothandel plaats in veilingen waaraan marktpartijen verplicht moeten deelnemen. Het ontwerp van die veilingen bepaalt dus zeer direct de efficiëntie van de handel. In Europa daarentegen hangt de efficiëntie van de globale markt niet noodzakelijk af van de efficiëntie van de veilingen georganiseerd door beurzen. Dit onderscheid is belangrijk voor de argumentatie die volgt. Daarenboven betekent dit dat de argumentatie niet noodzakelijk van toepassing is op alle veilingen.

Figuur 1 toont de verschillende beurzen in Europa.

Figuur 1: Europese elektrische energiebeurzen

III. Blokorders

Beurzen hebben naast uurorders ook orders die betrekking hebben op meerdere uren tegelijkertijd. Uurorders worden gekarakteriseerd door een bepaald volume (volumelimiet, typisch in MWh) dat wordt gevraagd of aangeboden voor een bepaald uur aan een bepaalde prijs (prijslimiet, typisch in €/MWh). Blokorders worden gekarakteriseerd door een volume dat wordt gevraagd of aangeboden voor een aantal opeenvolgende uren (grootte van het blok, typisch in MWh/h). Daarenboven wordt een blokorder in zijn geheel aanvaard of volledig geweigerd. Beurzen met uurorders en blokorders zijn bijvoorbeeld het Nederlandse APX, het Franse Powernext, het Scandinavische Nord Pool, het Sloveense Borzen, Oostenrijkse EXAA en het Duitse EEX.

Blokorders zijn belangrijk voor participanten maar ook voor de beurzen zelf. Aan de hand van blokorders kunnen marktpartijen hun kosten beter uitdrukken. Generatoren kunnen bijvoorbeeld de vaste kosten die gelinkt zijn aan het opstarten van een centrale beter in rekening brengen aan de hand van zo’n blokorder. Voor beurzen betekent deze extra flexibiliteit dat zij meer handel aantrekken in competitie met andere markten. Merk op dat in bilaterale markten contracten zo flexibel zijn als overeengekomen kan worden door de betrokken partijen.

Door de aanwezigheid van blokorders, is het niet vanzelfsprekend om het resultaat van de veiling te bepalen. Aangezien blokorders niet gedeeltelijk aanvaard kunnen worden, zijn binaire variabelen nodig om het veilingprobleem te modelleren. Modellen met binaire variabelen voor blokorders en continue variabelen voor uurorders zijn Mixed Integer Problemen (MIP) die moeilijk oplosbaar zijn. De beschikbare commerciële software om zulke problemen op te lossen heeft de laatste decennia een enorme ontwikkeling doorgemaakt, maar er blijft het fundamentele probleem dat in het slechtste geval alle combinaties moeten afgegaan worden. De tijd die een beurs beschikbaar heeft om een oplossing te publiceren is echter beperkt tot 10 à 30 minuten.

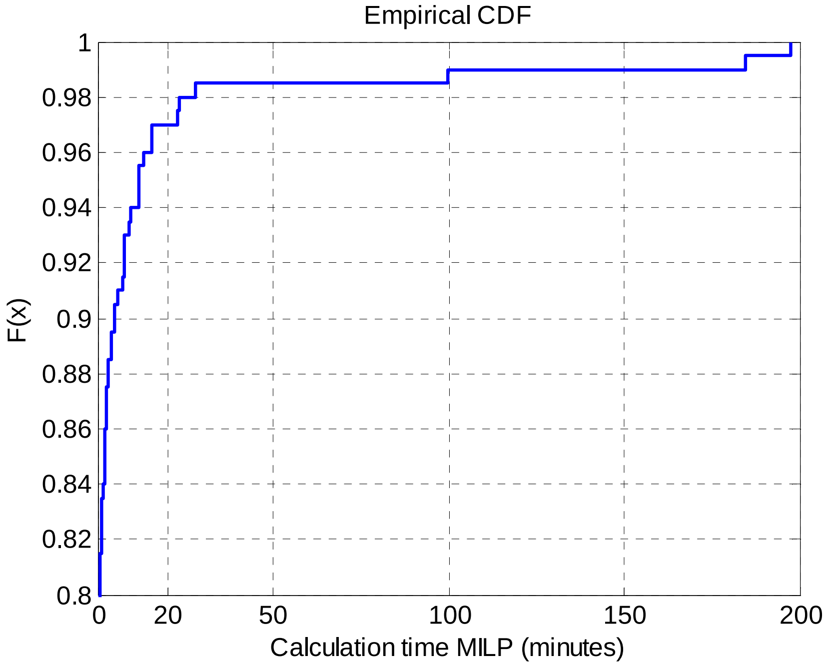
Daarenboven heeft een veiling met blokorders niet noodzakelijk een evenwichtsprijs. Dit is het gekend probleem van niet-convexe markten. Beurzen lossen dit probleem op door prijzen op te leggen die niet noodzakelijk evenwichtsprijzen zijn. Vraag en aanbod zijn dan niet noodzakelijk gelijk aan de bepaalde prijzen, maar de beurs forceert de gelijkheid. Blokorders die geld zouden kunnen verdienen indien ze aanvaard worden, worden bijgevolg mogelijk uitgesloten zonder dat zij daarvoor een compensatie krijgen. In deze tekst wordt naar zulke blokorders verwezen als ‘paradoxaal geweigerde’ blokorders (PRB).

Om de uitdagingen aan te pakken, werd het probleem met blokorders gemodelleerd als een optimalisatieprobleem met beperkingen. De verschillende oplossingen van dit model werden vervolgens bestudeerd in een ontworpen steekproef van representatieve scenario’s. De voornaamste besluiten van deze studie worden in wat volgt samengevat.

Numerieke complexiteit

De optimale oplossing van het veilingprobleem werd gemodelleerd met lineaire prijzen die niet noodzakelijk evenwichtsprijzen zijn, maar ook met niet-lineaire evenwichtsprijzen. Een veilingsysteem met niet-lineaire prijzen is een alternatief voor de aanpak die ingeburgerd is bij Europese beurzen en wordt in wat volgt verder besproken. Het model met lineaire prijzen heeft meer beperkingen. In deze studie werden die beperkingen als de voornaamste bron van numerieke complexiteit geïdentificeerd. Zonder die beperkingen kon het probleem opgelost worden binnen 1,4 seconden voor alle scenario's in de steekproef.

Met deze beperkingen, werd de software gestopt na 2,5 dagen in 2 scenario's omdat de optimale oplossing nog niet gevonden was. Voor alle andere scenario's in de steekproef van 200 scenario's is de rekentijd gemiddeld 4 minuten en altijd tussen een paar seconden en 3,5 uur (Figuur 2). Merk op dat tegen de verwachtingen in er geen statistisch significant verband werd gevonden tussen de numerieke complexiteit van het probleem en het aantal blokorders.



Figuur 2: Rekentijd voor alle scenario's in de steekproef, met uitzondering van de twee scenario's die gestopt werden na 2,5 dagen

De standaard praktijk van beurzen om snel tot een oplossing te komen bestaat uit het probleem op te delen in een blokorder selectiemodule en een coördinatie module die de prijs bepaalt voor een vaste blokset. Een speciaal ontworpen procedure zoekt dan binnen de beschikbare tijd een zo goed mogelijke combinatie van blokorders om te aanvaarden. De details van de procedures zijn niet publiek beschikbaar zodat ze niet geëvalueerd konden worden. Daarom werd de optimale oplossing vergeleken met de oplossing van een eenvoudig algoritme gebaseerd op de decompositie zoals toegepast door de beurzen. Gecumuleerd over de 200 scenario's genereerde de optimale oplossing bijna een half miljoen € meer handelswinsten voor de participanten. Dit onderstreept het belang van een goed ontworpen algoritme.

Merk op dat sommige beurzen eigenlijk een nog moeilijker probleem oplossen dan hetgeen gemodelleerd werd in deze studie. Het gaat om beurzen zoals het Franse Powernext die uurorders hebben met hellingen erin. Er zijn reeds solvers beschikbaar om zulke problemen op te lossen maar ze zijn nog niet vergaand ontwikkeld. Voor de simulaties in deze tekst is dus een abstractie gemaakt van deze complexiteit.

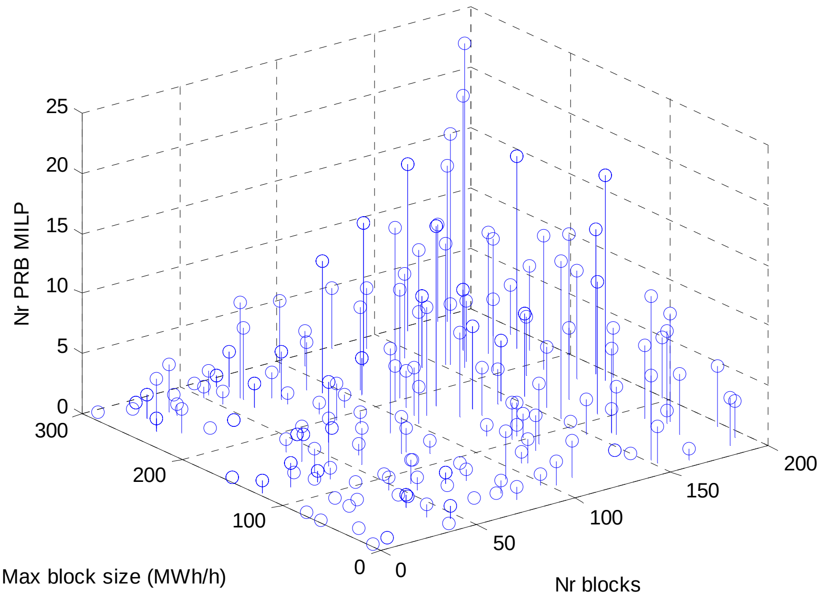
Blokorder beperkingen

De aantrekkelijkheid van blokorders in vergelijking met uurorders is een gevolg van de ondeelbaarheid en het feit dat ze meerdere periodes linken. Maar zoals hierboven uitgelegd, worden blokorders die willen handelen aan de vastgelegde marktprijzen mogelijk toch geweigerd. De mogelijkheid dat een blokorder paradoxaal wordt geweigerd is natuurlijk een minder aantrekkelijk kant van het product.

Paradoxaal geweigerde blokorders (PRBs) kunnen leiden tot klachten en in de limiet tot een verlies van vertrouwen in het product en de beurs. Dit verklaart mogelijk waarom beurzen het gebruik van blokorders beperken. Alle beurzen beperken het aantal blokorders dat per participant per dag kan worden ingediend of de grootte (MWh/h) van een blokorder en de opeenvolgende uren die kunnen gecombineerd worden in zo'n order (het aantal types).

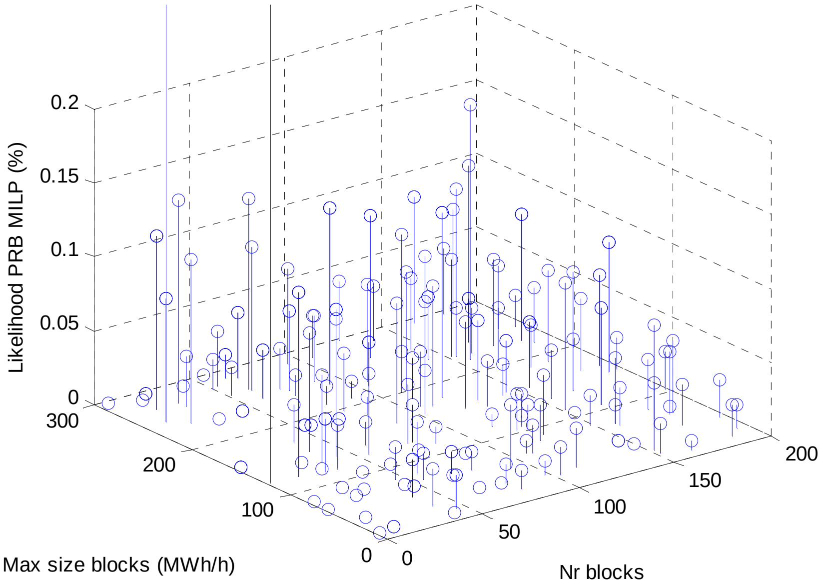
Een sensitiviteitsanalyse werd uitgevoerd op de steekproef van 200 scenario's, die bestaat uit scenario's met en zonder een type beperking, met een totaal aantal blokorders gaande van 1 tot 200 per scenario en een maximum grootte van blokorders in een scenario gaande van 10 tot 300MWh/h.

De analyse toont aan dat het aantal PRBs toeneemt met het aantal blokorders in een scenario (Figuur 3). Bovendien lopen kleinere blokorders minder risico paradoxaal geweigerd te worden. Maar dit op zichzelf is geen reden om alle participanten te verplichten tot het gebruik van kleinere blokorders. In de steekproef is de waarschijnlijkheid dat een klein blokorder (<50MWh/h) paradoxaal wordt geweigerd niet groter indien er ook grotere blokorders aanwezig zijn (tot 300MWh/h). Daarenboven is het risico sowieso klein (gemiddeld 4% in de steekproef).



Figuur 3: Aantal PRB (Z-as) in functie van het aantal blokorders (X-as) en de maximale grootte van de blokorders (Y-as) in een scenario

Tegen de verwachtingen in (Figuur 4), is de waarschijnlijkheid dat een blokorder paradoxaal geweigerd wordt niet groter indien het totaal aantal blokorders in een scenario groter is, noch indien er grotere blokorders van veel verschillende types zijn in een scenario. Daarom werd geargumenteerd dat het in het voordeel is van zowel beurzen als participanten de beperkingen op het gebruik van blokorders op te heffen. Deze beperkingen reduceren immers het volume dat verhandeld wordt op de beurzen en verplicht marktpartijen naar alternatieven te zoeken.



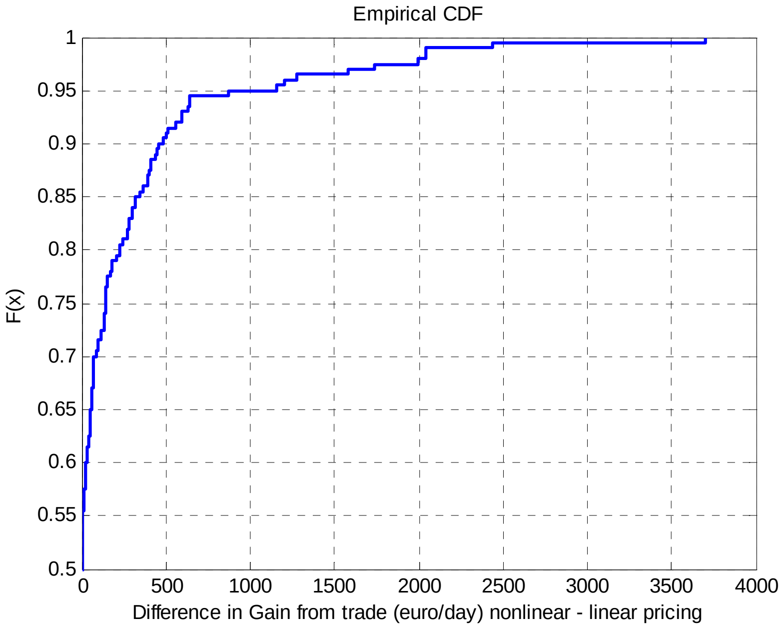
Figuur 4: Waarschijnlijkheid PRB (Z-as) in functie van het aantal blokorders (X-as) en de maximale grootte van de blokorders (Y-as) in een scenario

In deze analyse is wel abstractie gemaakt van de numerieke complexiteit. De situatie met veel blokorders en enkel een paar uurorders werd ook niet expliciet onderzocht. Met andere woorden, het is niet de bedoeling te beweren dat elke beurs van bij de start blokorders zonder beperkingen zou moeten toelaten. Bijvoorbeeld de Oostenrijkse beurs introduceerde nadat de markt een zekere maturiteit had gekregen pas blokorders na een jaar.

Prijsbepaling

Een veilingsysteem met niet-lineaire prijzen is een alternatief voor de aanpak die ingeburgerd is bij Europese beurzen. De meeste literatuur schrijft voor dat men in non-convexe markten best niet-lineaire prijzen toepast. De vraag kan daarom gesteld worden of beurzen in Europa best zouden overschakelen naar een systeem met niet-lineaire prijzen, zoals gesuggereerd in O'Neill et al. (2006).

Het belangrijkste argument in het voordeel van niet-lineaire prijzen is handelefficiëntie. Figuur 5 toont echter dat het verschil in handelswinst tussen de twee systemen klein is in de steekproef. In meer dan de helft van de scenario's is er geen verschil en het verlies in handelswinst door het opleggen van lineaire prijzen is nooit meer dan 3697€ in een scenario (0.05% van de totale handelswinst). Bovendien is de beursveiling slechts een van de mogelijke markten waarop marktpartijen contracten kunnen afsluiten. Licht inefficiënte handel op deze beurzen impliceert niet noodzakelijk dat de groothandelsmarkt in zijn geheel ook inefficiënt is.

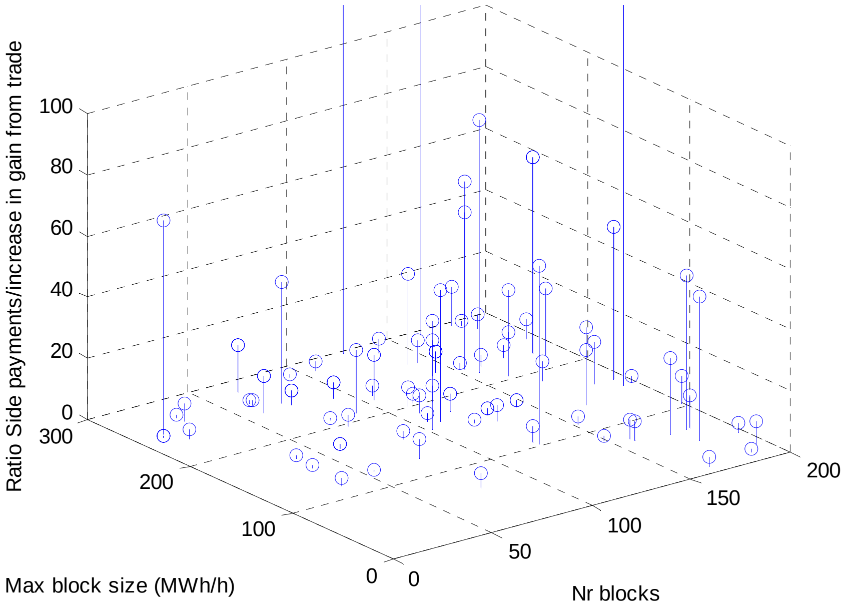


Figuur 5: Cumulatieve waarschijnlijkheidsfunctie van het verschil in handelswinst niet-lineair – lineair prijssysteem

Het belangrijkste argument in het nadeel van niet-lineaire prijzen is het noodzakelijk gebruik van discriminatoire betalingen. Aanvaarde orders die aan de vastgelegde uurprijzen geld verliezen en geweigerde orders die geld hadden kunnen verdienen indien ze aanvaard waren geweest, worden daarvoor gecompenseerd via een extra betaling. Die extra betalingen worden dan teruggevorderd van andere orders. Het probleem van zulke discriminatoire betalingen is dat ze niet afgedekt kunnen worden met financiële standaardproducten. Het komt erop neer dat een persoonlijke verzekering moet worden afgesloten, wat duur is. Daarenboven wordt een systeem met niet-lineaire prijzen als complex aanzien door marktpartijen en niet altijd goed begrepen. Ten slotte is het overschakelen naar een nieuw systeem op zich al kostelijk.

In de steekproef moeten in totaal 317393€ extra betalingen worden gemaakt. Dit is ruim 8 keer meer is dan de totale handelswinst die gerealiseerd kan worden door niet-lineaire prijzen toe te passen.

Figuur 6 illustreert de ratio extra betalingen over verschil in handelswinst per scenario voor de 97 scenario’s waarin er een verschil in handelswinst is. De maximale waarde van deze ratio is 1098 en in slechts 9 scenario's is de ratio kleiner dan 1. Merk op dat in 31 scenario's extra betalingen nodig zijn zonder dat dit handelswinsten oplevert.



Figuur 6: Sensitiviteit van de ratio extra betalingen onder het niet-lineaire prijssysteem over het verschil in handelswinst onder het lineaire prijssysteem

Er zijn dus duidelijke voordelen aan de aanpak die ingeburgerd is bij beurzen in Europa, terwijl het nadeel minder een rol speelt gezien participatie aan de beurs vrijwillig is en er handelsalternatieven zijn. Daarenboven werden de oplossingen onder beide prijssystemen vergeleken en is aangetoond dat voor elke € gewonnen in handelswinsten verschillende € extra betalingen nodig zijn. Merk op dat in een pool met verplichte participatie inefficiënte handel meer problematisch is zodat het nadeel van het lineaire prijssysteem zwaarder doorweegt.

Abbreviations

ARP	Access Responsible Party
CEER	Council of European Energy Regulators
CPUC	California Public Utilities Commission
CR	Congestion Revenue
DG	Directorate-General
EC	European Commission
EFET	European Federation of Energy Traders
ERGEG	European Regulators Group for Electricity and Gas
ETSO	European Transmission System Operators
EURELECTRIC	Union of the Electricity Industry
EUROPEX	Association of European Power Exchanges
FERC	Federal Energy Regulatory Commission
HVDC	High Voltage Direct Current
IEM	Internal Electricity Market
IFIEC	International Federation Of Industrial Energy Consumers
ISO	Independent System Operator
LMP	Locational Marginal Pricing
LP	Linear (Programming) Problem

LBA	Lower Bound performance Algorithm
LBAC	LBA with Centralized block order selection
LBAD	LBA with Decentralized block order selection
LESMAG	Leuven Electricity Spot Market Game
MIP	Mixed Integer (Programming) Problem
MILP1	MIP nonlinear pricing
MILP2	MIP linear pricing
NEC	Net Export Curve
NETA	New Trading Arrangements
NTC	Net Transfer Capacity
nTPA	negotiated Third Party Access
OMC	Open Market Coupling
Offer	Office of Electricity Regulation
Ofgem	Office of Gas and Electricity Markets
OTC	Over The Counter
PJM	Pennsylvania, New Jersey and Maryland
PRB	Paradoxically Rejected Block
PTDF	Power Transfer Distribution Factor
PX	Power Exchange
rTPA	regulated Third Party Access
SO	System Operator
TEN-E	Trans European Energy Networks program
TPA	Third Party Access
TSO	Transmission System Operator
TTC	Total Transfer Capacity
UCTE	Union for the Co-ordination of Transmission of Electricity

Chapter 1

Introduction and thesis motivation

1.1 Overview

There are two parts in this chapter. The first part introduces the problems and the main contributions of this study. The second part introduces terminology and highlights the changing context in which power exchanges operate. The readers less familiar with these concepts are advised to first read section 1.3.

1.2 Research subject

In this section, respectively the research subject is discussed and the main contributions to this topic are outlined per chapter.

1.2.1 Power exchange auction trading platform design

Power exchange

In the past the electricity industry was characterized by vertical integration and regulation. National transmission networks have been interconnected for mutual assistance, but not to be the backbone of an Internal Electricity Market in Europe. Introducing a market system in this industry is therefore not trivial. Furthermore, the competitiveness of this sector is important for the competitiveness of the whole European economy.

Therefore, it is of crucial importance to have a system that makes market functioning possible. The well functioning of the electricity market does not depend on the implementation of a power exchange. An exchange is only a part of the market system and perhaps not even strictly necessary. An exchange does not create competition where the market structure does not allow it. An exchange only facilitates trade by offering certain services via a trading platform. As such, it can only help reducing transaction costs and stimulate trade. However, a well functioning exchange is an indication of a more mature market (DG COMP, 2006).

Auction trading platform design

Exchanges are most known for the auctions they organize day ahead for every hour of the next day. In its role of auctioneer, the exchange receives orders and then decides which to accept and at which prices to settle the contracts. When taking this decision, it is not up to the exchange to question whether these orders actually reflect the costs or the values of their participants. The auctioneer selects the buyers who name high prices and the sellers who name low prices.

An auction can be implemented as a constrained optimization problem. The least contested objective to decide which orders to accept is to maximize the profits for participants. The participants' profits or gains from trade result from the demand side that has to pay less than its willingness to pay and the supply side that receives more than what it wanted to be paid.

Behavior of participants should be taken into account when designing the rules of the exchange, such as the format of the orders, the price rules, etc. As discussed in Stoft (2002), one way to arrange efficient trading is for all the traders to bid prices that are equal to their costs and values. If all bidders tell the truth, the outcome is efficient. For these reasons economists look for so-called incentive-compatible designs, but sometimes they are too complex or politically unpopular. In this case, a less efficient design will usually need to be adopted.

The study has been inspired and partly also made possible by research projects conducted for exchanges (Box 1-1).

Box 1-1: Industry funded project work

- At the beginning of this PhD in 2003, the research group ELECTA became involved in the task force of the Belgian TSO Elia that studied the possibility of creating an exchange in Belgium. In 2003, the group also started contributing to the research efforts of the APX Group (Encompassing the Dutch and UK power exchanges, but also several gas exchanges) investigating the implementation of market coupling. Since then, research in this area has increased as a consequence of some important events.
- September 2004, there was the cooperation agreement on the creation of the Belgian exchange, called Belpex. In cooperation with the Dutch APX and the French Powernext, Elia set up Belpex. It is the first time that 3 European PX will be linked with a day-ahead market coupling mechanism.
- December 2004, the Dutch regulator DTe approved the investment plans of the Dutch TSO TenneT and the Norwegian TSO Statnett to interconnect Norway and the Netherlands by a submarine HVDC cable. A condition for the approval of the NorNed cable was that it is to be used to couple the day-ahead auctions of APX and Nord Pool[1]. Nord Pool is the PX of Norway but also of Denmark, Finland and Sweden (December 2004).

1.2.2 Main contributions

The PhD of Boisseleau (2004) is an inspiring primer on European power exchanges. His text focuses on the role exchanges have in the creation of a single market in Europe, while this text is rather on auction implementation and functioning.

Chapter 2 essentially discusses that auction design does not always allow traders to express their costs. The aim of chapter 2 is to put in perspective the design common among exchanges in Europe. The power exchange design is compared with alternative designs that have been implemented elsewhere. The most relevant design experiences worldwide are discussed and a sample of relevant literature is provided.

Chapter 3 then illustrates for a simplified laboratory setting that even if the auction design allows traders to express their costs, they can have an incentive not to do so.

The following chapters focus on the implementation of the design that is prevailing in Europe. Most exchanges originally only organized trade within national borders. Increasingly, they are also involved in facilitating cross-border trade. The changing context implies new challenges but also renews the discussion on how former challenges have been addressed.

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[1] A case study on the NorNed cable, including a viewpoint on the application by Tennet and Statnett and the approval by DTe is provided in Meeus et al. (2005a).

The three main issues addressed are network constraints, block orders and political constraints. Besides the introductory chapters 1 and 2, the text is structured in three parts respectively dealing with network constraints (chapter 3 and 4), block orders (chapters 5,6.7 and 8) and political constraints (chapter 9). In what follows, the three parts are outlined:

Network constraints

Much literature has already been devoted to dealing with network constraints, but applying the auction problem with network constraints to exchanges is not straightforward.

Chapter 3 describes a laboratory on the competitive functioning of the European Electricity Market. In the laboratory, the students trade via an auction trading-platform with network constraints. The chapter introduces the auction problem with network constraints. The problem is modeled as a constrained linear optimization problem.

Chapter 4 applies the model introduced in chapter 3 to power exchanges, largely a European phenomenon. Existing commercial software can be used to solve the auction problem. However, the problem does not necessarily uniquely determine prices and quantities. This implies that the software that is used to solve the problem has a significant impact on the determination of the market outcome, which is of course unacceptable. The contribution of this chapter is to discuss this issue and potential solutions.

Block orders

The auctions organized by exchanges are hourly. Also the standardized orders are hourly and consist of a quantity that is offered or requested with a certain price limit. Besides these hourly orders, most exchanges also have block orders. A block order consists of a quantity that is offered or requested in multiple hours at an average price limit. Besides this inter-temporal rigidity, blocks also have a fill-or-kill constraint, meaning that the order has to be accepted completely or not at all.

Determining the market outcome in the presence of block orders is not straightforward. The indivisibility of block orders means that binary variables are necessary to model the auction problem. Models with binary variables for blocks and constrained continuous variables for hourly orders are Mixed Integer Problems (MIP), which are difficult to solve. The available commercial software has evolved substantially the last decades, but there is still the fundamental problem that in the worst case all combinations have to be enumerated to select the optimal solution, i.e. the problem is computational intractable.

Furthermore, a market-clearing price does not necessarily exist for auction with blocks. As will be discussed in chapter 2, this is because the auction with blocks is non-convex. Exchanges solve this problem by imposing linear prices that are not necessarily market clearing. The prices they determine do not necessarily equalize demand and supply, but the exchanges force the equality. More specifically, they exclude blocks that are in the money. In other words, blocks that want to trade as they can make a profit at the determined prices can be rejected without receiving a compensation for this lost trade opportunity. In this text, these blocks are referred to as Paradoxically Rejected Blocks (PRB).

The challenges of dealing with blocks are discussed by modeling the problem as a constrained optimization problem and analyzing the solutions in representative scenarios. Chapter 5 introduces the models that are used in chapters 6, 7 and 8. The chapter also introduces a batch of representative scenarios that has been designed to study auctions with blocks.

Chapter 6 analyses the computational complexity of the auction problem with blocks. This chapter introduces a simple but fast algorithm that finds a feasible but not necessarily optimal solution. The performance of this simple algorithm is a lower bound for the performance of the heuristics used in practice that are not publicly available. The batch of scenarios is solved with this simple algorithm and also optimally with commercial software to indicate the exposure to sub-optimal solutions when using heuristics. The results illustrate a significant gap between both solutions, both in terms of gains from trade and number of PRBs.

Chapter 7 analyses the rationale of block order restrictions. All exchanges restrict the size (MWh/h) or the type (span in terms of hours) or the number of blocks that can be introduced per participant per day. There is no methodology available to impose such restrictions. This can partly explain why all exchanges have very different restrictions. The contribution of this chapter is therefore to discuss the trade-off that exchanges need to make when imposing such restrictions and to provide recommendations. It is argued that the use of blocks is too restricted in practice.

Chapter 8 analyses an alternative pricing approach for an auction with blocks. To avoid PRBs, exchanges could apply nonlinear pricing. An auction with blocks is non-convex and most literature prescribes nonlinear pricing for non-convex auctions. The main argument is trade efficiency. The question is therefore raised whether exchanges should shift to nonlinear pricing, as suggested by O'Neill et al. (2006). In this chapter we show that the increase in gains from trade that could be achieved would be small relative to the large side payments that would be necessary under nonlinear pricing.

Political constraints

Chapter 9 analyzes the effect of political constraints on the auction problem with blocks and network constraints. Many of the market coupling proposals that are on the table are conceptual and do not include an implementation or model. Ehrenmann A. and Y. Smeers (2005) have already raised concerns on the implementation of network constraints in these proposals.

In these proposals, order books of different exchanges are not necessarily merged. The main reason is that exchanges are reluctant to completely share their order books[2]. As will be explained, a decentralized model cannot guarantee to find the optimal solution, even if enough time is available to enumerate all solutions. The contribution of this chapter is to indicate that decentralizing block order information reduces performance. Representative scenarios are solved using simple algorithms.

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[2] It is exchange's business to fix prices" and "order books contain valuable information about participants".

Box 1-2 discusses the papers on which the chapters have been based, acknowledging the colleagues that collaborated with me and helped developing these papers.

Box 1-2: Papers

http://www.esat.kuleuven.ac.be/electa/publications/search.php

http://homes.esat.kuleuven.be/~leonardo

- Chapter 1 is based on two papers: 1) "Development of the internal electricity market in Europe", a paper presented at the 2005 Regulatory Round Table of the Florence School of Regulation, and published in the Electricity Journal (Meeus, Purchala and Belmans, 2005) and 2) "Regulated cross-border transmission investment in Europe", a paper presented at the 2006 IEEE Transmission and Distribution Conference in Dallas and accepted for publication in the European Transactions on Electric Power (Meeus, Purchala, Van Hertem and Belmans, 2005).
- Chapter 3 is based on a working paper “Laboratory on the competitive functioning of the European Electricity Market” (Meeus, Willems and Belmans).
- Chapter 4 is based on a working paper "Complexity of price rules for coupled PXs and the use of LMP" (Meeus, Vandezande, Cole and Belmans, 2006).
- Chapter 7 is based on a working paper "Block order restrictions in combinatorial electric energy auctions" (Meeus, Verhaegen and Belmans, 2005).
- Chapter 8 is based on "Pricing electric energy auctions with blocks", a paper presented at the 2005 ETE Workshop on Market modeling of the Central Western European Market in Leuven, which has been revised to "Clearing auctions with block bids: linear versus nonlinear pricing" a paper pending at IEEE Transactions on Power Systems (Meeus, Verhaegen and Belmans, 2005).
- Chapter 9 is based on a working paper "Market coupling algorithm: centralized versus decentralized block order selection" (Meeus, Saguan, Glachant, Dessante, and Belmans, 2006).

1.3 Context

This section addresses the changing context in which exchanges operate. The aim of this section is to introduce terminology and concepts used in this text. Respectively, power systems, and the Internal Electricity Market in Europe are discussed.

1.3.1 Power systems

This section respectively discusses the delivery of a unit electric energy (kWh) and the European transmission system. The aim is the underline the relevance of network constraints.

1.3.1.1 Delivery of a kWh

Weedy (1998) provides an interesting discussion on the delivery of a kWh. Electric energy is a secondary product that cannot be excavated or mined. Production is done in so-called generation plants, the delivery points of the transport or transmission network. After generation, electric energy is brought to a higher voltage using transformers. Next, it flows through the transmission network to nodes where it is transformed into lower voltages for direct supply to large consumers or distribution and ultimately consumption at the load points of the network (Figure 1-1).

The characteristics of consumption or demand, generation and transport are essential in understanding the electricity system in its current form. Demand is characterized by low price elasticity, especially in the short-run. Demand is also highly variable and uncertain. The volatile nature of demand is partly explained by the seasons, days of the week and hours of the day. The International Energy Agency has forecasted a 1.4% average annual demand growth up to 2030 in Europe (EU-15).

As demand increased, larger generation units (economies of scale) have been increasingly connected to high voltage transmission lines forming grids that consequently have been interconnected. Diverse consumer groups (industrial/residential, geographic spread) have been linked to flatten the demand profile. At the location of consumption, the voltage is transformed to a consumer adapted voltage level. The more power needed, the higher the consumption voltage level.

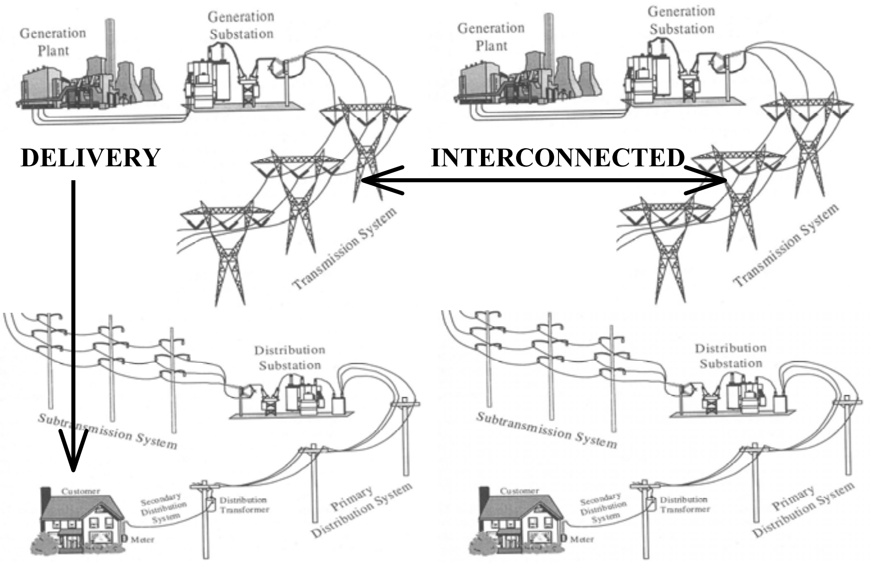

Figure 1-1 Interconnected power system

Historically, electric energy has often been centrally generated using hydropower, followed by a shift to engines and steam turbines, using primary energy sources such as coal, oil, gas, and uranium. More recently, there has been a shift towards distributed generation (Pepermans et al., 2005) and also Renewable Energy Supply (RES), mainly wind generators.

Electric energy is economically non-storable[3] so that generation and load (consumption + losses) have to be balanced at all times. Moreover, transmission of electric power is economically uncontrollable[4], meaning that energy flows distribute themselves over the transmission lines according to the impedances (Kirchoff's Laws). As a consequence, it is not trivial to manage the constraints of such a network[5].

The danger of a power system is that the failure of a single element can lead to the collapse of the whole system. To prevent blackouts, the network is designed and operated in such a way that it can absorb the breakdown of every single critical element, being line, consumer or generator, i.e. the so-called (N-1) contingency rule.

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[3] Note that Pumped Hydro and Compressed Air Energy Storage are an exception to this rule but they are not widespread due to geological constraints. As discussed in Cole et al. (2006), upcoming technologies have the potential to challenge the rule all together.

[4] The increasing penetration of power flow controlling devices is challenging this view, see for instance the discussion provided in Van Hertem et al. (2006).

[5] This problem is commonly referred to as congestion management. Purchala (2006) discusses congestion management in a market environment.

1.3.1.2 European transmission network

In the past, national networks have been interconnected for mutual support in the case of emergencies. The European network therefore consists of relatively strong national networks weakly interconnected across borders. Furthermore, it is made up of 5 synchronous areas[6], being UCTE on the continent, Scandinavian Nordel, Great Britain, Ireland and the area of the Baltic States. These areas are relatively weakly interconnected with High Voltage Direct Current (HVDC) links.

In other words, the European network has not been designed to be the backbone of the Internal Electricity Market (IEM). Besides serving the market, the network also has to ensure security of supply and to allow connecting renewables such as wind energy that are very demanding for the network.

From the beginning of the liberalization process, European authorities have recognized that an efficient use of the existing infrastructure in combination with network expansions is crucial. Figure 1-2 illustrates the bottlenecks as identified by the European Commission in the framework of the Trans-European Network for Energy program (TEN-E).

For detailed information on the priority project objectives and main elements, see the brochure of DGTREN (EC, 2004a). Meeus et al. (2005b) provide an overview of the regulatory environment in which these investments take place, concluding that the current regulatory framework is inadequate to deliver the necessary investments.

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[6] Note that in all of these areas there are Member States of the European Union but that there are also non-Member States in these areas. In comparison, the North-American network consists of 3 interconnected synchronous areas, being the East, the West and the Texas area.

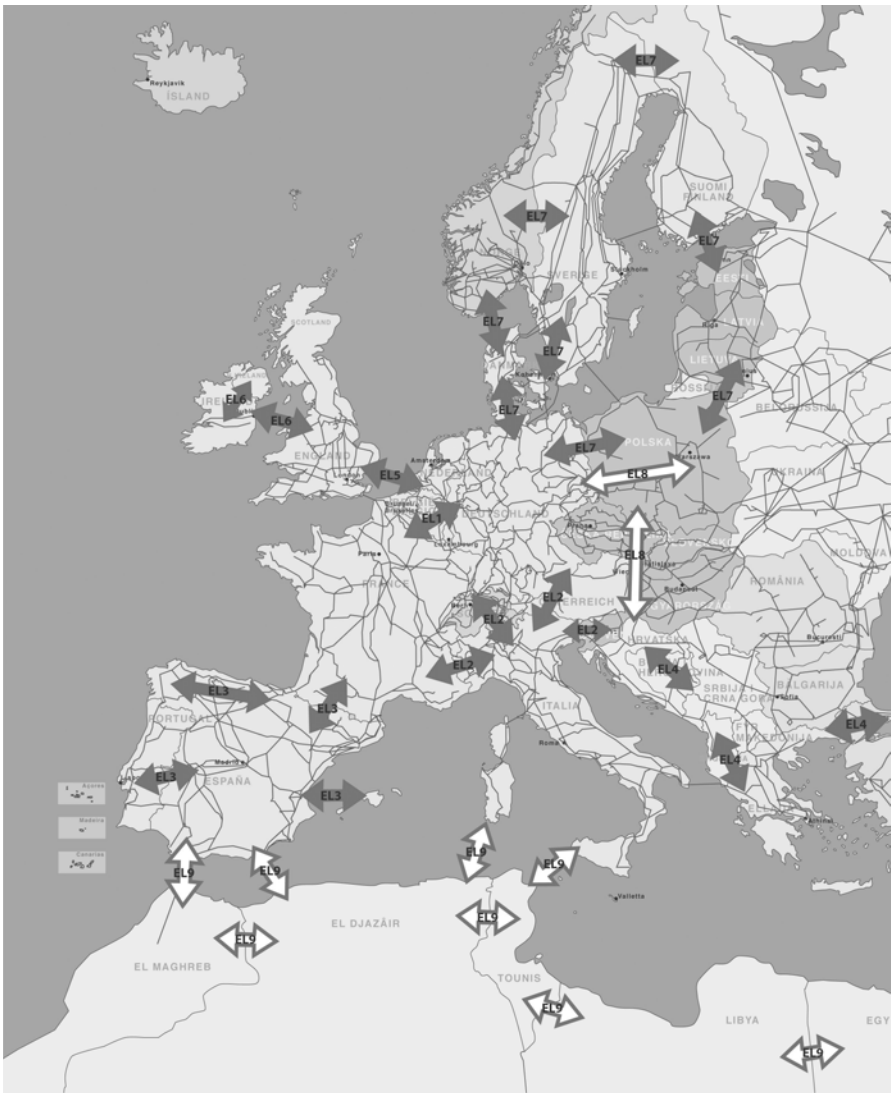

Figure 1-2: Axes for priority projects TEN-E program
(dark arrows EL1-7 agreed, light arrows EL8-9 additionally proposed)

1.3.2 Internal Electricity Market in Europe

The liberalization process in the European Union has gradually been progressing for 10 years. First, the legislation that guided this process is briefly summarized. Then, the resulting market architecture is described, discussing the role of power exchanges and introducing the auctions organized by these exchanges.

1.3.2.1 Legislation

In the past, the electricity industry has been vertically integrated, state owned and regulated. The growing ideological and political disaffection towards vertically integrated monopolies and the liberalization successes in other network industries like telecommunication, have lead to liberalization initiatives world wide in the electricity industry. Vertically integrated utilities have been unbundled and barriers to entry in generation and supply are being removed to create competition, seen as a vehicle to increase the economic efficiency of the electricity industry. For a discussion on liberalization, see for instance Littlechild (2001) and Newbery (2001).

The liberalization of the electricity industry in Europe started with the implementation of Directive 96/92/EC and was later accelerated with Directive 2003/54/EC. The liberalization is inline with the creation of an Internal Market in Europe with free movement of people, capital, goods and services, as determined by the European Treaties.

In what follows, the 3 major implementation[7] aspects of the Directives are discussed, being market opening, third party access and the system operator. As Hancher (1997) commented, Directive 96/92/EC allowed nearly everything, except an integrated internal market. The second Directive 2003/54/EC can however be characterized by shorter-term deadlines and less freedom:

- First, Directive 96/92/EC introduced the concept of eligible consumers, being consumers who have the legal capacity to contract volumes of electric energy from any supplier. The Directive aimed at a slow and gradual opening of the Member States' electricity markets so that more and more generators and consumers have the opportunity to freely negotiate the purchase and sale of electricity. With the new Directive 2003/54/EC, put into force in 2003 and replacing the first Directive, this process is accelerated: all non-households customers are eligible from 1 July 2004 and all consumers will be from 1 July 2007.
- Second, suppliers and generators need to be assured they will have access to the grid to settle negotiated electric energy transactions for delivering electric energy. Directive 96/92/EC included 3 third party access models, being negotiated third party access (nTPA), regulated third party access (rTPA), and the single buyer model. The single buyer model allows the creation of a mandatory power pool for generators with for instance the system operator acting as a 'single buyer' in the pool. In the rTPA model, prices for access to the network are regulated, while in the nTPA they may be subject to negotiations. Different access and tariff regimes have proven to be one of the main obstacles to the creation of the IEM (Roggenkamp and Boisseleau, 2005). Directive 2003/54/EC therefore imposes one regime, being rTPA, and the requirement to appoint a regulator, who has to approve tariffs, monitor congestion management methodologies and act as a dispute settlement authority.
- Third, the system operator plays a crucial role, also in a liberalized market. He provides the critical coordination services: keeping the balance between generation and supply, keeping the voltage at the right level, restart it when

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[7] The annual benchmarking reports of the European Commission provide an overview of the implementation status per Member State (e.g. EC 2005).

> it suffers a complete collapse, etc. Partially, the system operator carries out these basic functions by purchasing what are called ancillary services, which can be supplied by generators, but also by the demand side. In order to ensure transparency of the market and to avoid discrimination, network activities on one hand and supply and generation activities on the other hand have to be separated. While the first Directive required an administrative unbundling, only obliging companies to present a separate balance sheet for each activity, the second goes a step further requiring legal unbundling. Transmission and distribution companies respectively have to apply legal unbundling from 1 July 2004 and 2007 onwards.

Together with the Directive 2003/54/EC in 2003, Regulation 1228/2003 was issued. Regulation 1228/2003 is the first to address cross-border trading. The rationale behind it is to set harmonized principles on cross-border transmission charges and on the allocation of cross-border capacities.

The Directorate-Generals of the European Commission (EC) are responsible for developing and implementing European policies (The three DG's directly involved in the energy field are DG Transport and Energy, DG Competition and DG Environment). Twice a year they discuss the creation of the IEM at the Florence forum with the stakeholders. Some of the most important associations or organizations taking part in this debate are:

- The consumers (IFIEC);
- The European Regulators (ERGEG, CEER);
- The industry (Eurelectric);
- The system operators (ETSO, UCTE, Nordel, etc.);
- The traders (EFET);
- The power exchanges (Europex);

1.3.2.2 Market Architecture

Stoft (2002) defines market architecture as a map of its component submarkets including the type of each submarket and the linkages between them. The European legislation discussed in the previous section, imposes the conditions that should allow market functioning, but the implementation of a market architecture is a competence of the Member States.

Most European countries have chosen to keep centralized components to a minimum and to leave market organization to the dynamics of the private initiative. This has resulted in a market architecture as for example illustrated in Figure 1-3.

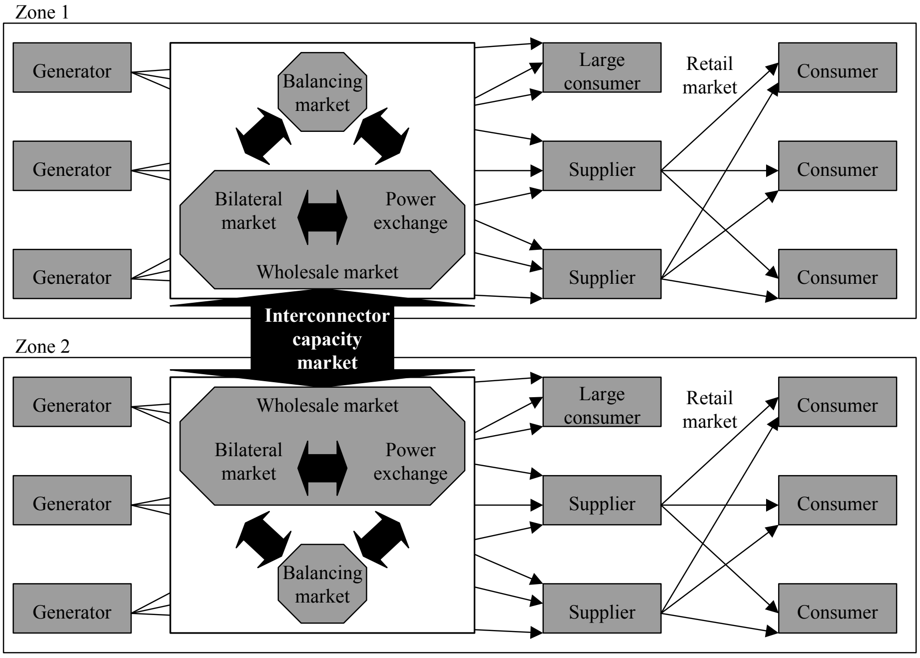


Figure 1-3: IEM market architecture

The entire Internal Electricity Market is divided into submarkets according to the control zones of the different Transmission System Operators (TSO). The control zones of a TSO mostly coincides with national borders, with exception of for instance Germany that has 4 TSOs. Figure 1-3 illustrates that the zonal division is also reflected in the average market prices. On average there are large price differences, with day-ahead wholesale prices going from 30€/MWh in the Scandinavian countries to 60€/MWh in Italy.

National markets can be seen as divided in balancing markets and wholesale markets. Finally, wholesale markets are further divided in bilateral markets and power exchanges.

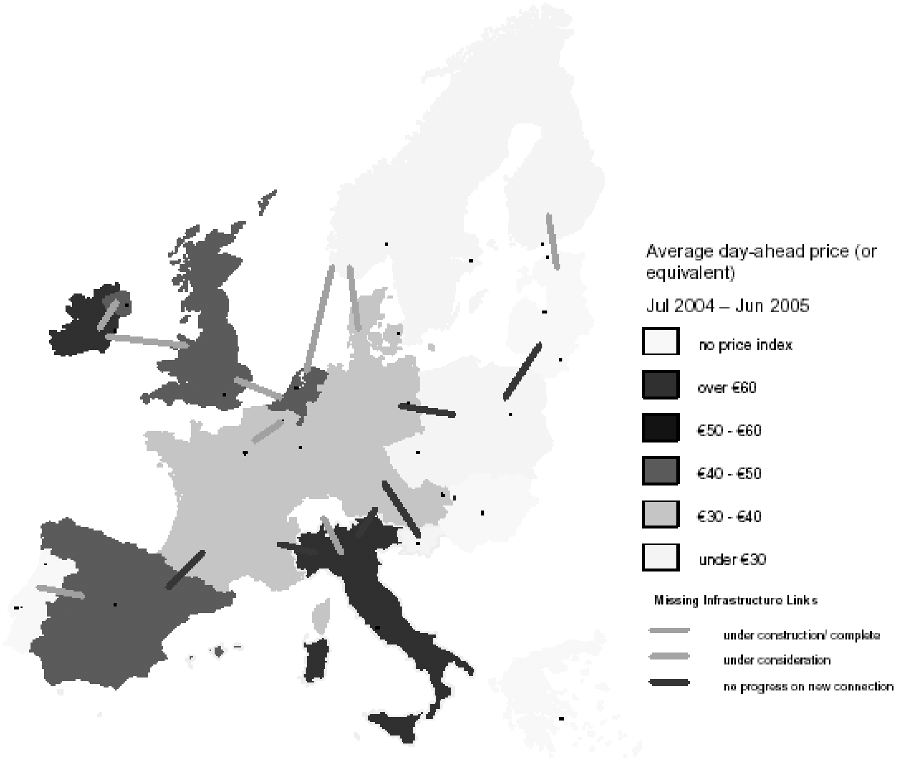


Figure 1-4: Average day-ahead price Jul 2004 –Jul 2005 DGTREN (2005)

1.3.2.2.1 National wholesale and balancing markets

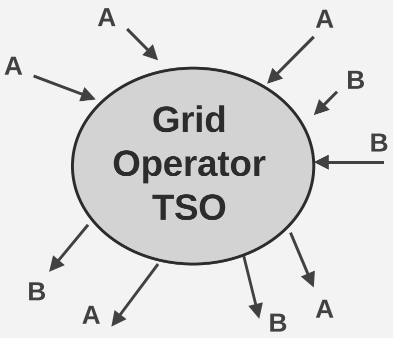
To explain the role of exchanges in the market, balancing and portfolio management are introduced in this section. Consequently the auctions organized by exchanges are introduced.

Balancing

Grid users or their business representatives are responsible for their individual balance. This means that generators have to match as well as possible what they generate with what they sell. Large consumers or suppliers try to match their consumption with what they purchase. Unbalances are discouraged with fines based on the cost of the regulating and reserve power the TSO procures from grid users to alleviate the overall unbalance in its control zone (Box 1-3).

The TSO also purchases other services to perform its tasks, such as reactive power support, black-start capability, etc. In general, these services are referred to as ancillary services or system services. The distinction with balancing services is not always as clear. In principle, the difference is that balancing services are paid by unbalanced grid users, while the costs of the other services are socialized, i.e. paid for by all users through the transmission tariffs.

Box 1-3 Balancing



- At *gate closure*, grid users (A,B) submit their intentions in terms of injections in and withdrawals or off-takes from the grid to the TSO:
  $\sum (\text{Cons}_A - \text{Prod}_A) = 0$
  $\sum (\text{Cons}_B - \text{Prod}_B) = 0$
- This process is often referred to as nomination.
- Grid users can choose to be represented by balancing managers, who aggregate several portfolios within one control zone. In Belgium, such balancing managers are called Access Responsible Parties (ARP).
- The TSO balances the overall system if needed, i.e. if $\sum_{A,B} \neq 0$
- Therefore, the TSO uses services purchased from grid users and settles the costs with unbalanced users per settlement period. The details of the balancing system are very different for every country, see for instance ETSO (2003). Payments for these balancing services are generally based upon availability and use, as the TSO procures options or rights to call upon regulating and reserve power at a certain strike price. Markets range from mandatory to purely commercial and from day-ahead offering to long term tendering. Settlement periods range from 15 minutes to 1 hour.
- Between gate closure and real time, conditions can change so that not all users are balanced. However, it is also possible that the unbalance is deliberate as the unbalance settlement is a real time price for electric energy.

Portfolio management

At the wholesale level, electric energy is traded several times before the actual delivery takes place. Trade takes place at prices that can vary substantially as expectations towards generation and consumption adjust based on the available information.

Most wholesale trade volume in the Internal Electricity Market is traded bilaterally. Bilateral trade means the negotiation of large tailor made contracts, but also trade in more a standardized type of markets, often called over-the counter (OTC) markets. Suppliers buy in advance using long-term contracts to cover their consumption portfolio (Box 1-4). As real consumption is not completely predictable and electric energy cannot be stored, there is also a need for additional daily and even hourly contracts in day-ahead or intra-day markets.

Box 1-4 Portfolio management

- To avoid being unbalanced in real time, market parties try to balance their portfolio. E.g. suppliers:
- Will forecast consumption of their clients as in Figure 1-5.
- Will typically purchase multi-year to monthly base load contracts, i.e. for delivery during the whole day for a certain period.
- Will typically still have an open position one day ahead of delivery. This is because their position has to be covered hour per hour and hourly forecasts become more accurate as real time approaches.
- One day ahead of delivery (D-1) this means that in some hours they will have purchased too much (D-1 Long) and in other hours they will have purchased too little (D-1 Short). As illustrated in the figure this position can for instance be very different during week days and weekends.

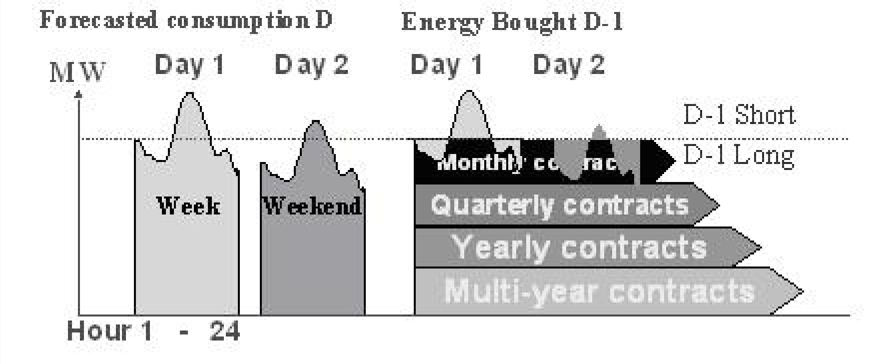


Figure 1-5: Managing a supplier portfolio

Power exchange

The closer to real time the more specific the needs are on the one hand, and the more difficult it is to find a counterparty on the other hand. Power exchanges offer a solution to this problem by providing automated trading platforms. Power exchanges are organized markets that typically facilitate trade in standardized hourly and multi-hourly contracts. They offer a centralized platform where potential traders can exchange electric energy. The exchanges provide several services:

- The exchange is the counter-party for all transactions. This means that traders do not have to worry about counterparty risk[8], i.e. risk of insolvency of their counterparty. Trade is therefore also anonymous so that participants do not necessarily expose their net position by participating on the demand or on the supply side.
- The exchange has simple rules to match and settle contracts, i.e. there is no time consuming negotiation of prices or discussion of contract details.

A mixture of private and public initiatives by market parties and TSOs has lead to the creation of a PX in most countries in Europe[9] (Figure 1-6).

Figure 1-6: European Power Exchanges

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[8] To hedge the risk of a counter-party that does not pay, exchanges often asks traders for bank guarantees and sometimes cooperate with a clearinghouses.

[9] In some countries even more than one PX has been created.

The volumes traded on the exchanges (Figure 1-7) are still relatively low, with the exception of the Spanish and the Scandinavian exchange. However, these relative higher volumes on the Omel and Nord Pool can be partly explained by 'liquidity supporting measures':

- In Spain, only generators that transact through the exchange receive a capacity payment, i.e. a payment for making generating capacity available.
- In the Scandinavian countries, the exchange has cross-border trade exclusivity. How this works will be explained in section 1.3.2.2.2

The hourly prices on the exchanges are extremely volatile, which can be partly explained by the relatively low trading volumes, but also by the characteristics of electric energy, such as non-storability. Figure 1-8 illustrates the price evolution on the different exchanges. Note the figure shows the monthly average prices and not the hourly prices, which are even more volatile.

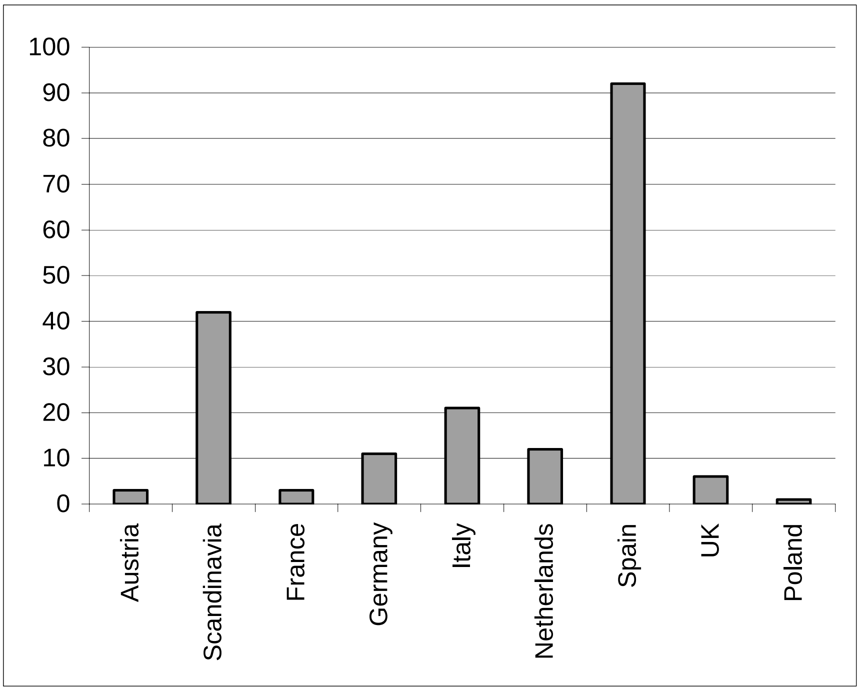

Figure 1-7: Trading volumes on the day-ahead Power Exchange markets % Total Consumption (DGTREN, 2005)

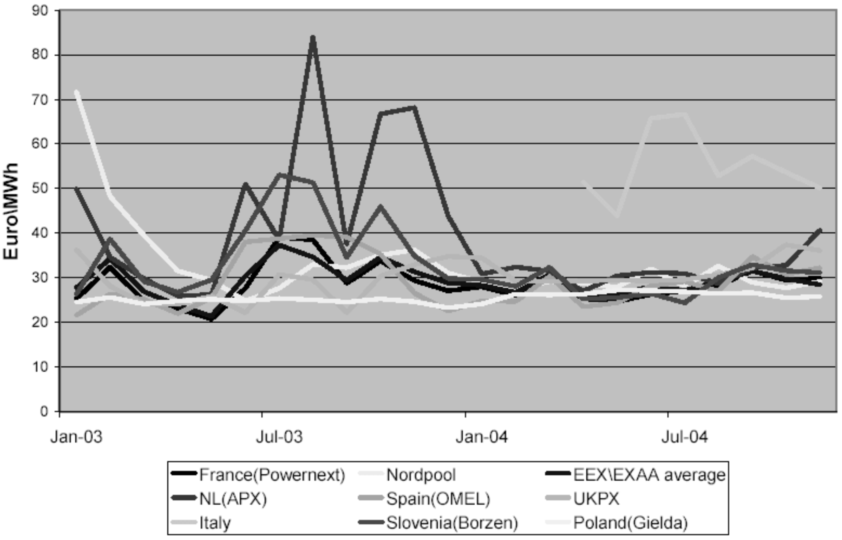

Figure 1-8: Monthly average price evolution on European Power Exchanges (day-ahead prices, DGTREN, 2005)

Auction

Power exchanges in Europe are most known for their auctions that run one day ahead of delivery for every hour of the next day. Often these exchanges also organize intra-day trade and even continuous financial markets for monthly, quarterly and annual futures contracts (Box 1-5). However, in the remaining of the text, power exchange refers to the institute organizing the auction, or the auction itself.

Figure 1-9 illustrates how such an auction functions. First, the market opens and traders can submit their orders. Then, the market closes, the orders are aggregated in demand and supply curves according to merit order and the market clears at intersection of these curves. Finally, the results are published and the transactions are settled. Order submission is typically in the morning and the markets close around noon. Results are then published 10 minutes to 1 hour after closure.

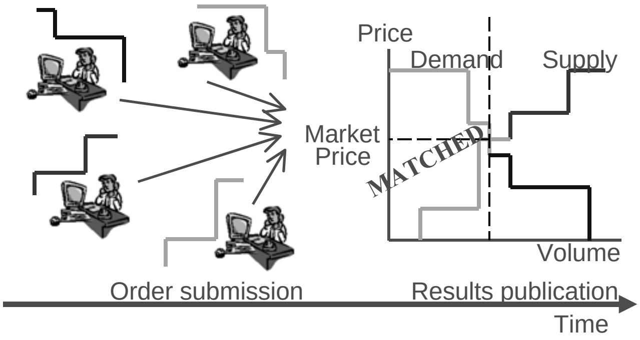

Figure 1-9: Power exchange auctions

These auctions are different from the auctions we all know, such as flower auctions, the auctions of radio licenses or Internet based auctions such as e-bay. Also mainstream auction theory cannot be directly applied to power exchanges, as it restricts attention to the sale of a single item. A very readable introduction can be found in Klemperer (1999).

The auctions organized by power exchanges are

- Double sided: there is demand and supply side bidding by generators, suppliers, traders, large consumers, etc.
- Multi unit: orders are typically expressed in MWh for delivery or off-take in a certain hour of the next day
- Uniform priced: all orders are settled at the same price
- Sealed bid - Single round: order books are not disclosed and orders cannot be changed.

Box 1-5 Continuous trade

- Continuous trade platforms allow traders to post bid and ask prices for a standardized product. The bid price is the highest price any buyer is willing to pay for a given product at a given time. The ask price is the lowest price that any trader has declared that he/she will sell a given product for.
- The standardized product can for instance be the delivery of 1 MWh for a whole year, starting next year.
- Figure 1-10 illustrates a continuous trade market in which traders post bid and ask prices. The price is discovered at time T1 where the first deal takes place and rediscovered at time T2 when the next deal takes place.
- Note that the UK power exchange (UKPX) and several gas exchanges do not have organize auctions but offer a continuous trade platform.

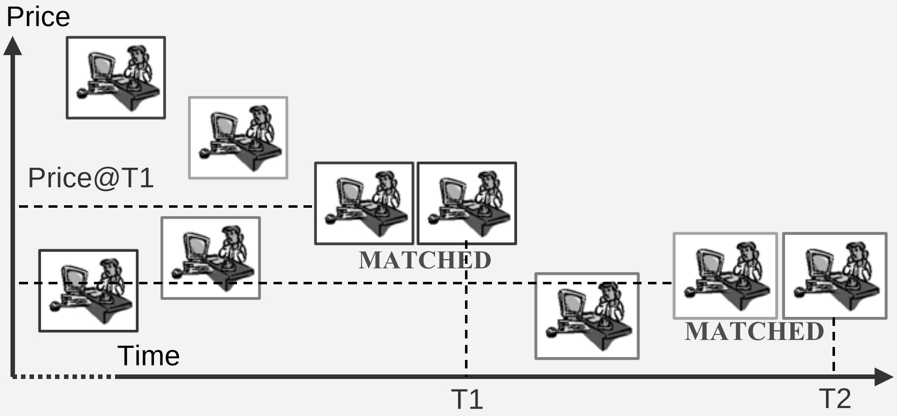

Figure 1-10: Illustration of continuous trade

1.3.2.2.2 *Linkages between national markets*

In Europe, most TSOs do not avoid but only resolve intra-zonal congestion; counting on the fact that congestion does no easily occur within the control zones. Because cross-border interconnection capacity is scarce, inter-zonal congestion is also avoided as much as possible by restricting cross-border trade. Cross-border trade is constrained by allocating a limited amount of transfer capacities via interconnector capacity markets (Figure 1-3).

Interconnector capacity markets

On most European borders, these interconnector capacity markets are implemented as explicit or implicit auctions (Figure 1-11). Under explicit auctioning, cross-border capacities are allocated to individual market participants, who can use these capacities to arbitrate between electric energy markets, i.e. to trade on price differences. Under implicit auctioning, cross-border capacities are not allocated to individual market participants. Rather, arbitrage is internalized in the mechanism for a coordinated clearing of different electric energy markets.

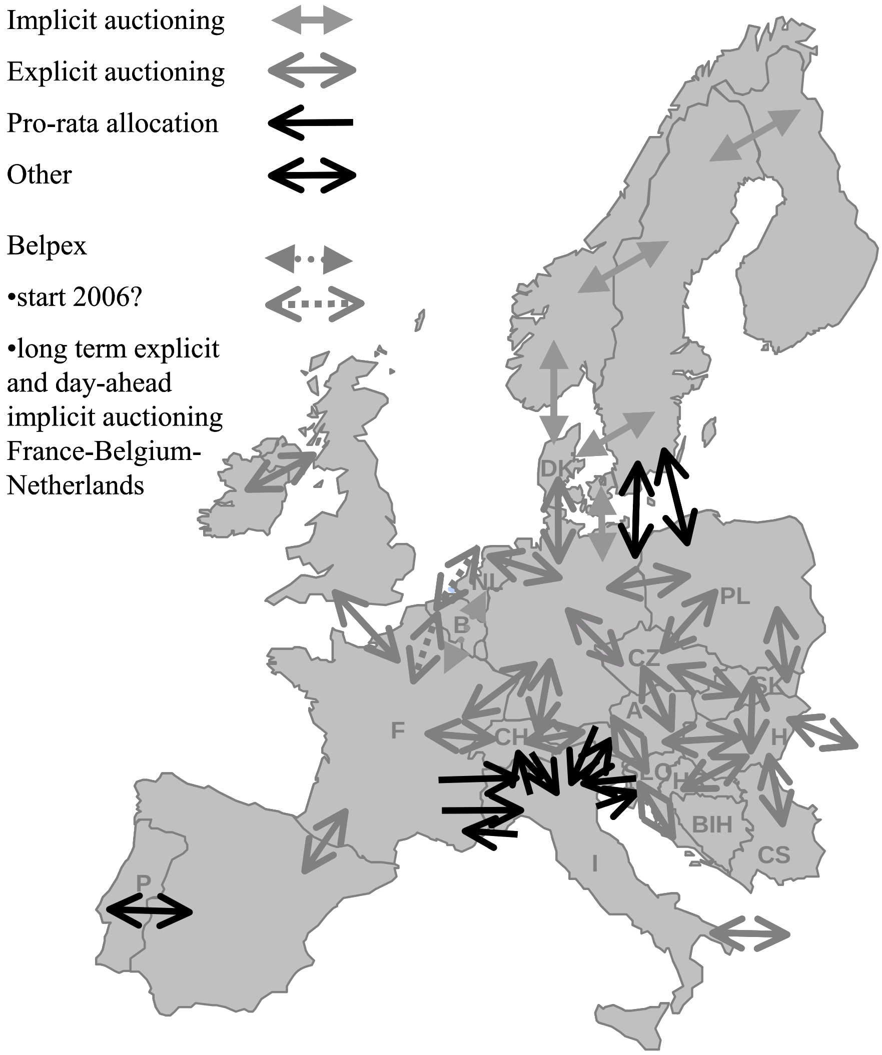

Figure 1-11: Cross-border capacity allocation end 2006[10]

Implicit auctioning in Europe is referred to as market coupling. Market coupling is best described as market clearing in international context with network constraints. Note that the term market coupling wrongly suggests that it is about coupling markets that were previously not coupled. In Europe, it is about replacing the explicit allocation of transfer capacities in separate interconnector capacity markets

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[10] Illustration is based on a illustration in a presentation of Electrabel.

by a system where exchanges can use the capacities to optimize the clearing of orders introduced to their auctions. For instance France, Belgium and the Netherlands are currently implementing such an initiative (Figure 1-11) and more of these initiatives have been announced.

Example (based on example in EC, 2004b)

To illustrate the difference between explicit and implicit auctioning, consider the following example with two markets A and B (Table 1-1):

- In market A, 100MWh is requested at 80€/MWh and 20MWh is requested at 30€/MWh. Generator 1 (G1) offers 50MWh at 20€/MWh and Generator 2 (G2) offers 100MWh at 40€/MWh.
- In market B, 110MWh is requested at 90€/MWh, Generator 3 (G3) offers 60MWh at 25€/MWh and Generator 4 (G4) offers 110MWh at 60€/MWh.

Table 1-1: Load and generation at market A and B

Market A	Market B
Load	
100MWh@80€/MWh	110MWh@90€/MWh
20MWh@30€/MWh	
Generation	
(G1) 50MWh@20€/MWh	(G3) 60MWh@25€/MWh
(G2) 100MWh@40€/MWh	(G4) 110MWh@60€/Mh

When both markets are isolated, Figure 1-12 and Figure 1-13 illustrate the aggregated curves of market A and B respectively. Market A would clear at 40€/MWh, market B at 60€/MWh. When the orders of the two exchanges are aggregated (Figure 1-14), the fully integrated market AB would clear at a price between 40 and 60€/MWh. In what follows we assume it clears at 50€/MWh.

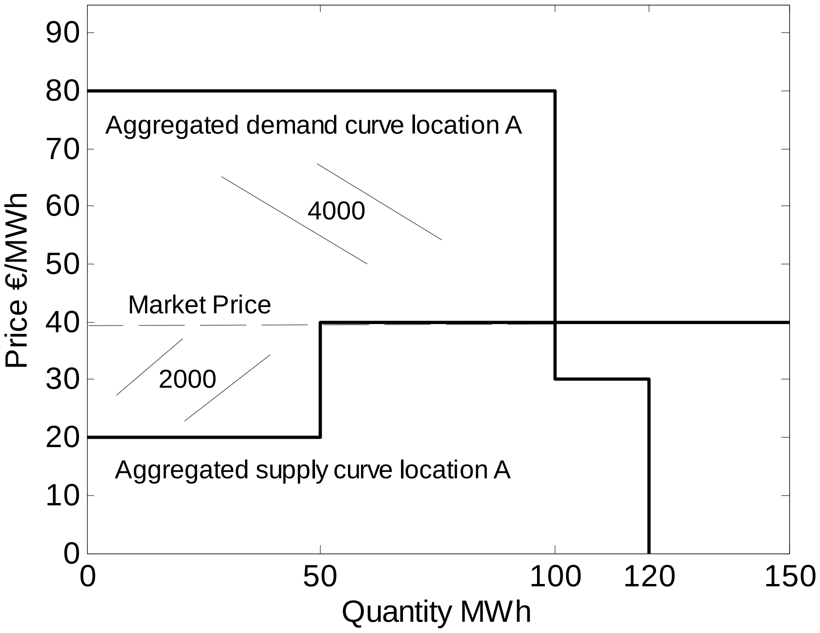

Figure 1-12: Market A isolated

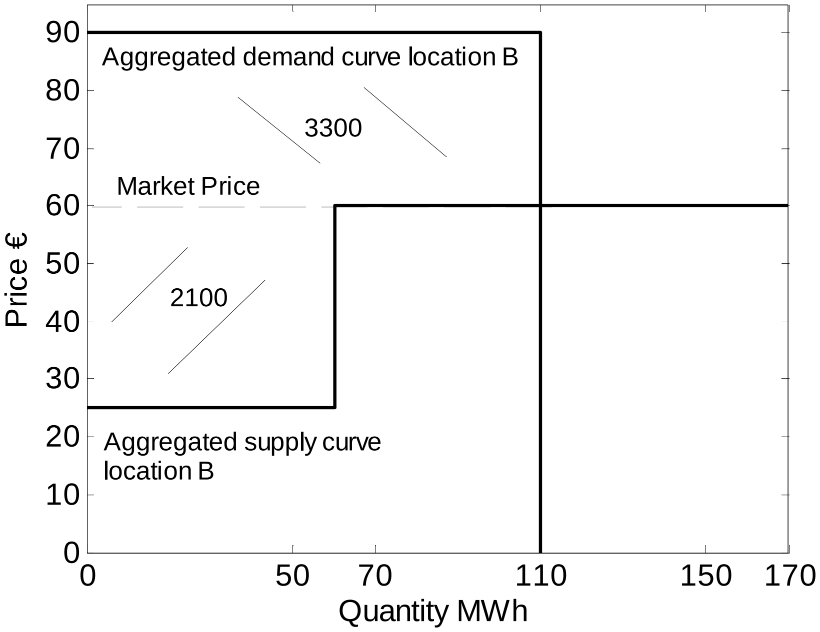

Figure 1-13: Market B isolated

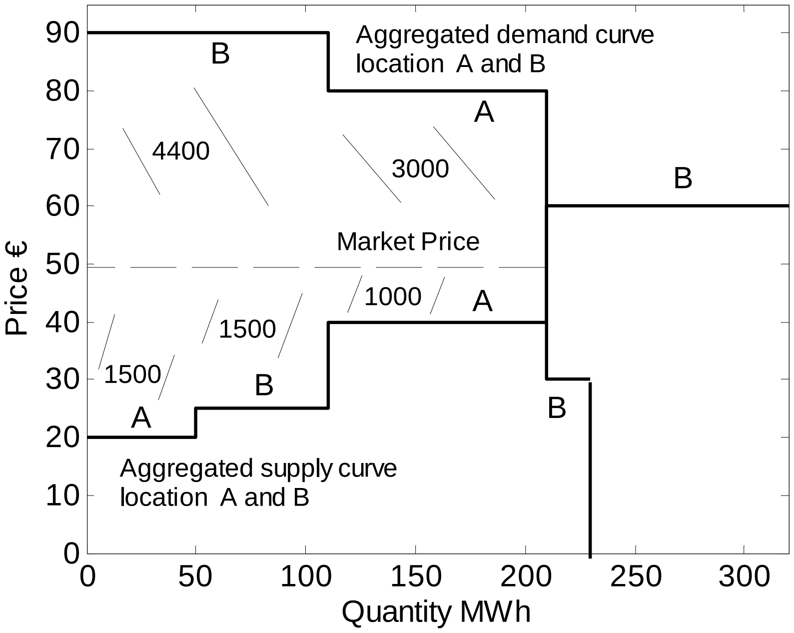

Figure 1-14: Fully integrated market (AB)

In the isolated market situation (Table 1-2), surplus at market A is 5000€ and 5400€ on market B. This surplus results from generators that are paid more than requested and from load that has to pay less than the willingness to pay. For instance at market A, G1 offers to supply 50MWh at 20€/MWh and the offer is accepted at 40€/MWh, meaning that G1 makes a profit of 1000€ (=(40-20€/MWh) x50MWh). This profit is called producer surplus, while gains from trade of the demand side are called consumer surplus and the sum surplus.

This total surplus is the surface between the demand and supply curves, which is also referred to as net utility, i.e. brut utility (the surface under the demand curve) minus the cost of supply (surface under the supply curve). Note however that in the next chapters, the term gains from trade is used, as orders received by exchanges do not necessarily represent the actual costs of generators or the actual values that consumers attribute to electric energy.

In the fully integrated market situation, total surplus increases because the same load is supplied with cheaper generation. G2 is accepted for an extra 50MWh at the expense of G4. The increase of surplus compared to the sum of the surplus of the separate markets, equals the difference in price between the orders (20€/MWh) times the 50MWh, which is 1000€. In other words, integrating these markets increases surplus.

Table 1-2: Surplus per participant and market at the given market prices

(Surplus €)	Isolated markets A and B		Fully integrated market AB	
	A (40€/MWh)	B (60€/MWh)	A (50€/MWh)	B (50€/MWh)
Load A	4000		3000	
Generator (G1)	1000		1500	
Generator 2 (G2)	0		1000	
Load B		3300		4400
Generator 3 (G3)		2100		1500
Generator 4 (G4)		0		0
Total	5000	5400	5500	5900
	10400		11400	

The fully integrated market solution means that generation is larger than load in market A, and vice versa in market B.

- At location A, generation is 150MWh, while load is only 100MWh.
- At location B, generation is 60MWh and load is 110MWh.

The difference (50MWh) is then exchanged. Assuming that markets A and B are two locations (A and B) that are interconnected by a line and that these markets are hourly markets, 50MW will be injected in the grid at A and 50MW will be withdrawn from the grid at B during this hour resulting in a flow of 50MW on the interconnecting line. In other words, the fully integrated market solution can only be possible if 50MWh can be transferred from A to B.

In the following two sections, it is assumed that only 40MW is available to explain the difference between implicit and explicit auctioning.

Implicit auctioning

Under implicit auctioning, a market operator (e.g. exchange) maximizes surplus subject to network constraints (e.g. imposed by the TSO). The next chapter models this problem. In this example it means that instead of 50MWh, only 40MWh can be transferred from A to B.

Therefore, Generator 4 at market B (60€/MWh) will be accepted for 10MWh instead of the cheaper Generator 2 at market A (40€/MWh), whose order becomes curtailed. Brut utility is unchanged but the cost of supply increases with 200€ (=(60-20€/MWh) x40MWh), meaning that net utility or surplus decreases with 200€.

The remaining surplus is 11200€. The marginally accepted (curtailed[11]) orders of G2 and G4, respectively 40 and 60€/MWh set the price is market A and B. At these prices, the market operator, who is counterparty for all transactions, will therefore have a net pay-off different from zero:

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[11] I.e. partly accepted. For instance G2 offers 100 MWh but only 90 MWh is accepted.

- At location A, more generation than load is accepted so that the operator pays more than he receives. He looses 1600€ (=40MWhx40€/MWh)
- At location B, more load than generation is accepted so that the operator receives more than he pays. He wins 2400€ (=40MWhx60€/MWh)

The net pay-off for the operator[12] is equal to 800€ (=2400-1600€). Note that this net pay-off is called congestion revenue and its use falls under Regulation 1228 (Box 1-6).

Box 1-6 Congestion Revenue

- If congestion revenue were profit for the TSOs, their profit would decrease from investing in the grid, giving them the wrong incentives.
- Therefore, Regulation 1228 limits the use of congestion revenue to either investment in the grid, a reduction of transmission tariffs or offering firm transfer capacity to the market.
- Meeus et al. (2005a) argue that there should be guidelines to determine the choice between the alternative uses for congestion revenue; otherwise this will lead to under-investment in the grid as regulators are biased towards a short-term tariff reduction.

Explicit auctioning

Under explicit auctioning, the 40MW transmission capacity would be auctioned in a separate capacity market. With perfect foresight, bidders for transfer capacity would predict the market outcomes with efficient use of the capacity. In the example, they would correctly predict the market prices of 40€/MWh at location A and 60€/MWh at location B and would therefore not bid more than 20€/MW per hour (i.e. 20€/MWh) for transfer capacity between the two locations. Under perfect competition, they would bid 20€/MW. The market operator would then receive 800€/MWh from explicitly auctioning this capacity, which is the same as under implicit auctioning.

Note that explicit arbitrage implies that a trader that acquired the transfer capacity will bid in the energy market. Assuming that the traders will introduce price taking bids in both markets to avoid unbalance penalties, the situation in the energy markets is as follows:

- At the low price market A: the trader introduces a price taking supply offer of 40MWh, meaning that the supply curves shifts to the right in comparison with the isolated situation. As illustrated in Figure 1-15, the resulting market price is 40€/MWh.

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[12] This net pay-off is called congestion revenue. In Europe, the use of this revenue is falls under Regulation 1228/2003. See Meeus et al. (2005b) for a discussion of this regulation.

- At the high price market B: the trader introduces a price taking demand bid of 40MWh, meaning that the demand curve shifts to the left in comparison with the isolated situation. As illustrated in Figure 1-16: the resulting market price is 60€/MWh.

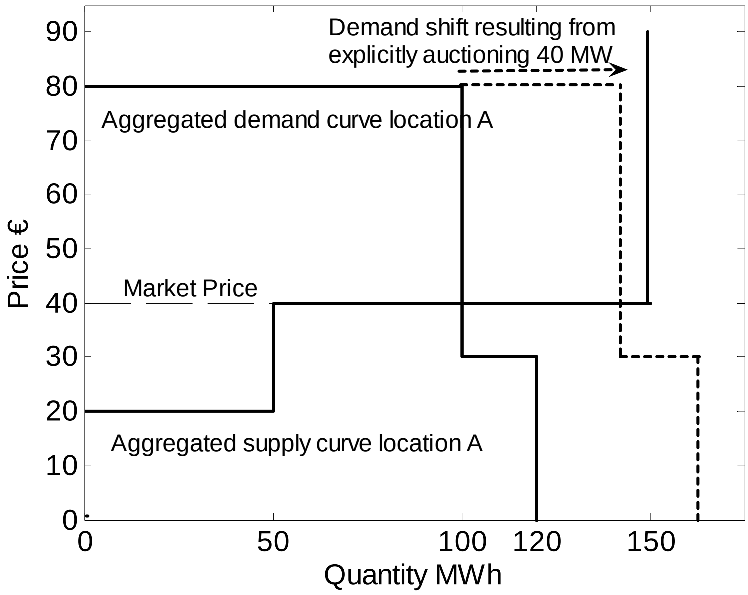

Figure 1-15: PXA under explicit auctioning (40MW A-B)

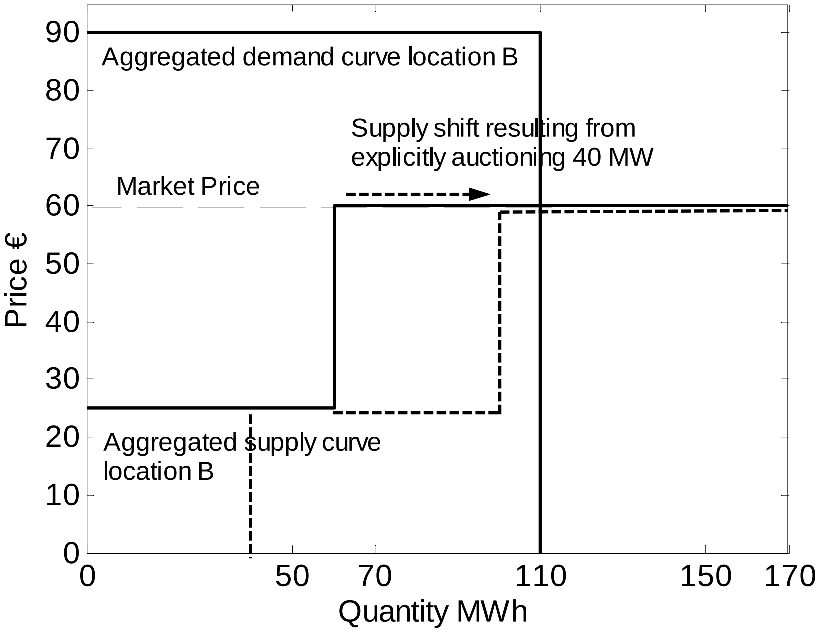

Figure 1-16: PXB under explicit auctioning (40MW A-B)

Note that in this example, the outcome of the market under explicit auctioning is the same as under implicit auctioning. The prices are the same and the same generators are supplying the same quantities in the two markets. Furthermore, the consumer and producer surplus and congestion revenue are equal. Both provide efficient locational signals. In the example, the signal is to invest in generation at B or to shift consumption from B to A. At the same time an investment signal is given to the TSO as a 10 MW increase of transfer capacity yields an increase in surplus of 200€.

However, explicit and implicit auctioning are not necessary the same under more realistic assumptions, e.g. imperfect competition. Chapter 2 provides a sample of relevant literature on the difference in design between implicit and explicit auctions.

Flow based auctioning

More important than the difference between explicit and implicit auctioning, is whether the approach is flow based or not.

As illustrated in Figure 1-11, the allocation of cross-border capacities on most borders is explicit. Furthermore, the allocation is done independently per border, i.e. not flow based. Note that even if the allocation is jointly as is the case for the internal borders of the Scandinavian countries, the approach is not necessarily flow based. The implicit auctioning approach applied in that region assumes that the underlying network is radial, while it is not.

The fact that dependency between borders exists or that the network is meshed [13] instead of radial is considered implicitly by reducing the capacities that are made available on European borders. This is necessary because even if no capacity is made available to contractually transfer electric energy over a certain border, contractual transfers in other parts the network can cause physical flows on that border. In highly meshed networks, it is even possible that these physical flows are as high as the available capacity on that border.

In the current non-flow based system, every TSO independently calculates Net Transfer Capacities (NTC) (Box 1-7) for its borders and distracts the capacities that are reserved for long-term historical contracts (Box 1-8). What remains is then made available to the market. As argued above, NTCs are actually a prudent underestimation of what is available. Therefore, a more coordinated flow based approach would imply a more efficient use of the scarcely available network capacities.

Box 1-7 Calculation of NTCs

- NTC values are typically used for flow gates or virtual lines that interconnect two zones, while physically several lines interconnect the zones and potentially also different loops interconnect the two zones.
- The NTC is the Total Transfer Capacity (TTC) corrected for a reliability margin.
- TTCs are calculated starting from a base case. Production on one side of a flow gate is increased and equally decreased on the other side until a network constraint is met. The TTC is then the total cross-border flow. The implementation of this scheme is discussed in Haesen et al. (2004).
- Indicative NTC values for winter and summer are published every year by ETSO. Note that these are respectively based on the base cases of the third Wednesday of January and June at 10.30 a.m.
- There is no harmonized calculation methodology. Two TSOs can have different values for the same flow gate, in which case ETSO (http://www.etso-net.org) publishes both, but eventually the minimum of the two is imposed on both TSOs.
- The multilaterally agreed 2004 Operations Handbook of UCTE (http://www.ucte.org) did not change this, as it explicitly describes three alternative TTC calculation methodologies.

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[13] There is more than one path between two locations.

Box 1-8 Historical long term contracts

- In the pre-liberalization period, long-term contracts with foreign generators were sometimes preferred over authorizing the construction of a new domestic plant. Often this was because of different national policies towards nuclear power; countries pro-nuclear then signed export contracts to countries contra-nuclear.
- These supply contracts also included a guaranteed network access. This meant that these contracts could also involve transit countries.
- In a liberalized context, less capacity can be made available for cross-border trade by the TSO due to these contracts.
- Recently (press release No 53/05 7 June 2005), the Court of Justice ruled that "The grant of preferential access to the cross-border electricity transmission network to an undertaking which previously held a monopoly, because of contracts concluded prior to the liberalization of the market, amounts to discrimination prohibited by the second electricity Directive." in Case C-17/03 against the Dutch company Samenwerkende ElektriciteitsProductiebedrijven NV (SEP).
- This led to an increase of the capacity auctioned by the involved TSOs, e.g. 350MW extra was auctioned on the French-Belgian border (Elia newsletter 21 oct 2005).
- Note that this ruling only has an effect on the SEP-contract, but creates a precedent for all other contracts and a lot of uncertainty in the mean time.

Chapter 2

Introducing market design via the characteristics of electric energy auctions

2.1 Outline

Market design can explain how market parties behave in that market. However, market parties do not necessarily behave perfectly competitive in a perfectly designed market. Their behavior is largely driven be the market structure. Still, a badly designed market can make it easier for them to misbehave or can even make it impossible to behave perfectly competitive.

As discussed in the previous chapter, most power exchange auction-trading platforms in Europe have a similar design and the main contributions of this text are on the implementation of that design. However, the aim of this chapter is to discuss this prevailing design by comparing it with alternative designs that have been implemented elsewhere.

The chapter starts by discussing the main design characteristics of electric energy auctions organized worldwide. The chapter then comments on different designs that are prevailing in Europe and the US, by arguing that the two designs are not necessarily that different.

2.2 Main design characteristics of electric energy auctions

Table 2-1 illustrates the main design characteristics of some of the most well-known electric energy auctions worldwide. The auctions are often categorized into exchanges and pools, although there is no unique way of doing this. By means of illustration, the definition proposed in Roggenkamp and Boisseleau (2004) is included in the Table. However, also these authors recognize that in practice every auction design differs.

Most designs are close to what can be called a pure power exchange or a pure power pool. Under the strict definition, only PJM would be a power pool and only CalPX would be an exchange. Under a less strict definition:

- Nord Pool, APX, Powernext, EEX, EXAA can be called exchanges.
- UK Pool can be called a pool.
- Omel and GME are a bit of both.

Note that the Californian exchange (CalPX) and the UK Pool are not operational anymore. Still, it is interesting to discuss these auctions, as most of the market design literature applied to electricity markets has been devoted to their design.

Table 2-1: Main design characteristics electric energy auctions

	Participation	Non-convexities		Network constraints	
	Mandatory?	**Multi-part orders?**	**Nonlinear pricing?**	**Implicit auctions?**	**Nodal?**
Power Exchange	**No**	**No**		**No**	
CalPX (US)	No[1]	No		No	
Nord Pool (Scandinavia)	No[2]	Yes (blocks)	No	Yes	No
APX (Netherlands)	No[3]	Yes (blocks)	No	No	
Powernext (France)	No	Yes (blocks)	No	No	
EEX (Germany)	No	Yes (blocks)	No	No	
EXAA (Austria)	No	Yes (blocks)[4]	No	No	
Omel (Spain)	No[5]	Yes	No	Yes	
				No[6]	No
GME (Italy)	Yes	No		Yes	
				No[7]	No
Power Pool	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
PJM (US)	Yes	Yes	Yes	Yes	Yes
UK Pool	Yes	Yes	Yes	No	

1 Mandatory for the three largest utilities

2 Mandatory for international trade

3 Mandatory for day-ahead transfer capacity

4 Not from start

5 Participation encouraged with capacity payments

6 Omel takes into account network constraints but in case of intra-zonal congestion in Spain, demand pays for redispatching.

7 GME takes into account network constraints and in case of intra-zonal congestion in Italy, Italy can be split up in predefined generation price zones, but a single demand price is imposed.

2.2.1 Participation

There is a debate on bilateral versus pool based trading arrangements. Pool based trading arrangements mean that all trade is centralized in an auctions, i.e. participation to that auction is mandatory. This was for instance the case for liberalization pioneers England and Wales, Alberta (Canada), Chile, Argentina and Pennsylvania, New Jersey and Maryland (PJM) in the United States.

More recently in California and also in Europe, market systems based on bilateral trade have been implemented. Under bilateral trading arrangements, wholesale trade takes place in several market types of which auctions are one. Participation to these auctions is voluntary.

In 2001, the regulator[14] in the UK replaced the Pool (England and Wales) by a market system based on bilateral trade. Several authors have analyzed this change in design as a shift from a uniform to pay-as-bid (discriminatory) price auction[15]:

- Wolfram (1999) argues against the reforms, saying that switching to discriminatory pricing is unlikely to solve the problem of high prices in the UK given the market structure, which is dominated by a small number of generating companies.
- Bower and Bun (2000, 2001) even suggest that the reforms would actually increase prices. Their results are based on an agent-based simulation model. The reason, they argue, is that market prices are not publicly available and agents with a large market share gain a significant informational advantage in a discriminatory auction, thereby facing less competitive pressure.
- The results in Fabra et al. (2004) are based on a multi-unit auction model. They present an analysis inline with the view of the regulator.

Also in 2001, the CalPX commissioned a report by leading auction theorists on the advisability of a switch from uniform to a discriminatory auction format for its day-ahead auction. In other words, there the discussion was not on participation, but on the pricing rules of the voluntary exchange. Still, it is relevant as the same literature on uniform versus pay-as-bid pricing was used as input for this discussion. Kahn et al. (2001) advised CalPX not to switch to a discriminatory auction, adding: *"In these dramatically altered circumstances, the suggested remedy we were called upon to evaluate has paled in significance."*

Note that both pricing rules are commonly used in financial and other markets, and there is now a voluminous economic literature devoted to their study (Binmore and Swierzbinski, 2000). However, also in other industries, there is no consensus on which is best.

2.2.2 Network constraints

The design choices related to network constraints are part of the debate on how to incorporate the network constraints into the electric energy trading arrangements. First, there is a debate on the degree of abstraction that can be made of the underlying physical network, i.e. zonal versus nodal. Second, there is a debate on the allocation of the network capacity. Depending on the allocation mechanism, the energy and capacities are integrated (implicit auctioning) or there is a separate capacity market (explicit auctioning).

2.2.2.1 Network abstraction

In Europe, intra-zonal or national network constraints are not taken into account in the trading arrangements. As explained in the previous chapter, TSOs only constrain cross-border trade, i.e. a zonal system. Therefore, for wholesale trade it is as if the

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[14] At that time called Offer, now called Ofgem.

[15] The pool is classified as uniform price because successful bidders all receive the same price for multiple units of output. The bilateral system is a discriminatory auction with successful bidders receiving prices for each unit of output equal to the prices they actually bid.

national networks have no constraints. These constraints are dealt with in real time and the cost of alleviating intra-zonal congestion is socialized among grid users.

In a nodal system as in PJM, all network constraints are taken into account in the trading arrangements and every node can have a different price in the wholesale market. Most European countries have a single price zone. Even Germany, which has 4 control zones, only has one price zone. Exceptions are Norway, which can be split up in two price zones, and GME (Italy), which can be split in several price zones, although a single price for demand is retained.

Several authors have analyzed the difference in design between a zonal and a nodal system, e.g.:

- Stoft (1998, 1999) presents a game theoretic analysis of the zonal design. He considers strategic behavior of market players who take unanticipated advantage of market rules. The author explains and illustrates how generators with high costs can get paid not to generate in a zonal system. As also discussed in Hogan (1999), generators have incentives to cause intra-zonal congestion to get paid for redispatching their plants. This will raise the short-run cost to loads and will encourage inefficient entry of new generation.
- Glachant and Pignon (2005), referring to the zonal Scandinavian market, argue that TSOs have an incentive to avoid intra-zonal congestion by over-constraining inter-zonal transfers. By over-constraining inter-zonal transfers, TSOs can hide the need for intra-zonal network investments.

Most European exchanges organize trade in electric energy nationally. In a system with national price zones, this means that they do not take into account network constraints. Omel is an exception. The Spanish exchange takes into account the intra-zonal network constraints, but in such a way that from a design point of view, Spain is a single price zone. First, Omel determines a single intra-zonal price for Spain. Second, Omel redispatches generators to deal with intra-zonal network constraints. Third, the costs are socialized with a general mark-up (cost increase) called uplift. In other words, the costs are socialized via the wholesale prices, instead of via the transmission tariffs. Therefore, these market rules exhibit the same problematic incentives as in a zonal system where the exchanges do not take into account network constraints.

2.2.2.2 Network capacity allocation

As explained in chapter 1, most European TSOs allocate the available cross-border capacities in separate interconnector capacity markets. The Scandinavian countries are the exception with Nord Pool that implicitly auctions all capacities made available by the TSOs on the internal interconnections of Norway, Sweden, Denmark and Finland. Also PJM has implemented implicit auctioning.

Several authors have analyzed the difference in design between a system with explicit and implicit allocation, e.g.:

- As argued in EC (2004b), explicit auctions can yield inferior outcomes due to the time lag between the clearing of the explicit auction and the exchanges. This is the case if an event, happening after the transfer capacity is purchased but before it is used, changes its value. Furthermore, under imperfect information, bidders for transfer capacity could even contract capacity and arbitrate in the wrong direction based on erroneous price forecasts.

- It has also been argued that implicit auctioning mitigates some opportunities of exercising market power, as for instance illustrated in EC (2004b) and modeled in Gilbert et al. (2004) and Ehrenmann and Neuhoff (2003). Neuhoff (2003) also gives empirical support in favor of implicit auctions, using the example of the German-Dutch interconnection.
- Willems (2002, 2004) on the contrary provides a simple example where implicit auctioning is sub-optimal under imperfect competition. The author notes that the paper is not meant to compare implicit with explicit auctioning. Still, the example shows that implicit auctioning does not always reduce market power.

Europe is moving towards a system with implicit allocation of network capacity. Concerns can however be raised related to some of the proposals that have been made to implement implicit auctioning in Europe. The political constraints of these proposals are discussed in chapter 8.

2.2.3 Non-convexities

In a convex market, generators do not have any fixed costs, have strictly increasing variable costs and can produce at any output level between zero and their capacity limit. Figure 2-1 illustrates a convex market. A price, p*, defined by the (unique) intersection of supply and demand curves, clears the market, i.e. demand equals supply at that price. Total gains from trade are then maximized at the market-clearing price. Also participants' gains from trade have been exhausted at p*, meaning that all the consumers that value consumption at p* or more are being supplied and every producer that is called upon to produce, is doing so profitably.

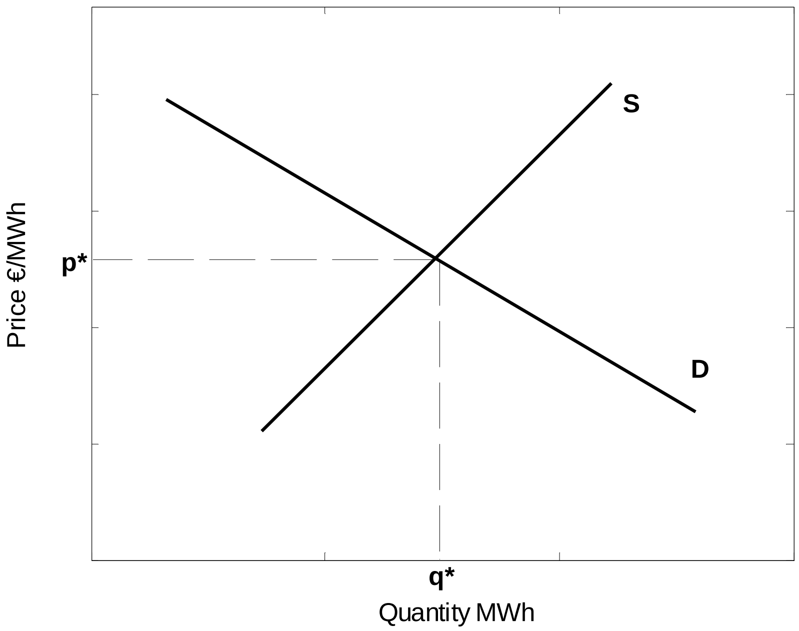

Figure 2-1: Convex market

In electricity markets, generators have startup costs, as well as minimum output levels, etc. Therefore, the electricity market is a market with non-convexities. In a convex market, a market-clearing price as in Figure 2-1 does not necessarily exist. Consider the following example with start-up costs, taken from Elmaghraby et al. (2004).

- Suppose there are four sellers in the market, each with a positive startup cost, associated with generation (Table 2-2).
- Assume that market's inverse demand curve is given by: $P(q) = 6 - q/2$.
- The sellers express their startup costs in multi-part orders.

The determination of the efficient dispatch is discussed in the section 2.4. The efficient dispatch solution is the solution that maximizes total surplus for this market. In this solution, seller 2 supplies 4MWh to the market. Sellers 1, 3 and 4 should produce nothing. The marginal valuation of energy by consumers at 4MWh is 4€/MWh ($P(q=4) = 6 - q/2$). The market price should therefore be 4€/MWh (maximally). However, this solution is not profitable for Seller 2. The cost for Seller 2 of supplying 4MWh is 19€ (=7€+4MWh*3€/MWh). Therefore, seller 2 wants to be paid at least 4,75€/MWh (=19€/4MWh).

This is essentially the problem caused by non-convexities in a market. In this example, the optimal solution in terms of total surplus cannot be settled with a uniform price, as this price needs to be at least 4,75€/MWh, but not more than

4€/MWh. Therefore, there is no uniform market-clearing price that the market finds by itself. The auction design can ignore non-convexities such a start-up costs, or can allow participants to express them, which means that the auctioneer has to deal with this problem.

Table 2-2: Costs and capacities for four generators

Generator	Seller 1	Seller 2	Seller 3	Seller 4
Energy cost (€/MWh)	2	3	5	6
Start-up cost (€)	10	7	4	3
Max quantity	3	4	4	4

2.2.3.1 Multi part orders and nonlinear pricing

For instance the UK Pool and PJM allow generators to submit the minimum and maximum output levels of their plants, the start-up costs, variable costs and ramping rates, i.e. multi-part orders.

Therefore, these auctioneers can be faced with the problem illustrated in the previous section. Pools, such as the UK Pool and PJM typically solve that problem by applying nonlinear pricing, meaning that contracts (q) are settled at an hourly reference price (p) in combination with an extra payment (EP): EP + pq.

There are many ways to implement this approach. The most extreme form is pay-as-bid, meaning that all accepted orders are settled at their order price or price limit (p=0 and A = order price limit). The approaches used by power pools are however very different from pay-as-bid. Most trade is settled at the hourly reference prices (EP=0), but some contracts are settled at these prices in combination with a discriminatory payment, i.e. side payment (EP>0). In other words, not all contracts are settled at the same average price, i.e. nonlinear pricing.

As an illustration, assume an hourly reference price of 4€/MWh for the above example. At this price, seller 2 has a deficit of 3€ (=19€-4MWhx4€/MWh). Under nonlinear pricing, this deficit will then be compensated with a side payment of 3€. Next, the 3€ needs to be recovered from the demand side. A market-up or uplift of 0.75€/MWh (=3€/4MWh) is not possible as demand at 4,75€/MWh (=4+0,75€/MWh) is smaller than 4MWh. Therefore, two-part tariffs need to be used, transferring consumer surplus to supplier 2. Consumer surplus is 4€ (=(6-4€/MWh) x4€/MWh/2), while only 3€ needs to be recovered. A possibility is to charge demand in proportion to surplus.

It is important to note that such charges will create additional incentives for the charged parties to distort their bids from true costs (see O'Neill et al., 1993). If the charge is related to the demand volume (EP(q)) instead of a uniform charge on demand, as in the example, this can distort the market and reduce surplus. Furthermore, side payments can also be necessary to compensate non-scheduled generators that could have made a profit. To clear the market, they also have to be compensated, but again this can create wrong incentives.

2.2.3.2 Single part orders and linear pricing

In California (CalPX) and in Italy (GME), the auctioneer does not allow its participants to submit multi-part orders. Orders are single part, implying that the auctioneer can simply stack up orders according to merit order and clear the auction at intersection of the aggregated demand and supply curves, as in Figure 1-9.

The easy solution for the auctioneer is indeed to ignore the non-convexities in the market. However, in such a system trading is more difficult for market parties. Even if generators want to, they cannot directly express their costs. Figure 2-2 illustrates demand versus the aggregated variable cost curve of the example in Table 2-2. This would be the supply curve if sellers simply submit their energy costs in the example.

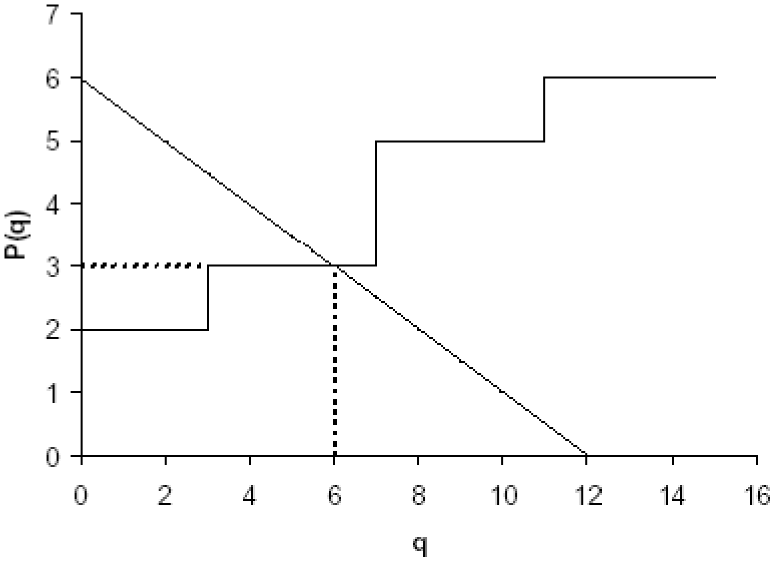

Figure 2-2: Demand versus aggregated variable cost curve (Elmaghraby et al., 2004)

In Figure 2-2, the auction clears at a price of 3€/MWh and 6MWh would be traded. Sellers 1 and 2 produce 3MWh, while sellers 3 and 4 do not produce. At these production quantities both seller 1 and 3 are asked to produce unprofitably. Seller 1's profit is equal to –7€ (=(3€/MWh – 2€/MWh)* 3MWh – 10€) and seller 2's profit is –7€ (=(3€/MWh – 3€/MWh)* 4MWh – 7€). Stoft (2002) provides more examples.

Obviously, generators have a clear incentive to include their start-up costs into the single part bids. As discussed in Stoft (2002), this kind of 'justified gaming' is difficult to distinguish from gaming in the meaning of exercising market power. As a result, it becomes more difficult to monitor abuse of market power in these auctions. Market power and abuse of market power are discussed in the next chapter on the competitive functioning of the European Electricity Market.

Some have argued that auctions with multi-part orders are necessary for the efficiency of electricity markets (Elmaghraby, and Oren, 1999; Elmaghraby, 2005). Others have suggested using multi-round auctions[16] with single instead of multi-part orders (Wilson, 1997). However, these studies tend to assume that auctions are mandatory. In a mandatory system, the outcome of the auction determines the dispatch of generators. In a bilateral based market, traders can iteratively adjust their portfolio by trading in consecutive markets. Therefore, inefficient trade in an auction with voluntary participation is not necessarily a problem. Note that the effect of having multi-round auctions is similar to having many markets.

2.2.3.3 Block orders and linear pricing

As discussed in the previous chapter, the auctions organized by European exchanges are hourly. Also the orders are hourly and consist of a quantity that is offered or requested with a certain price limit. Besides these hourly orders, most exchanges also have block orders. European power exchanges with block orders are APX (Netherlands), Powernext (France), EEX (Germany), EXAA (Austria), Borzen (Slovenia) and Nord Pool (Norway, Sweden, Denmark and Finland).

A block order consists of a quantity that is offered or requested in multiple hours at an average price limit. Besides this inter-temporal rigidity, blocks also have a fill-or-kill constraint, meaning that the order has to be accepted completely or not at all. Note that blocks can be introduced on the supply as well as on the demand side. Note also that Omel is an exception in Europe. Omel has multi-part orders instead of blocks.

In comparison with the single-part or hourly orders of exchanges, blocks allow traders to some extend to express their multi-period cost structures. However, blocks are not as flexible as the multi-part orders. For instance, blocks do not allow generators to directly express their fixed costs. As an illustration, assume that seller 2 wants to introduce a block order in the above example (Table 2-2) and assume that there are two periods. To be sure he earns back his costs if the block order is accepted, he could do the following:

- Introduce a 1MWh block with a price limit of 6,5€/MWh. His variable costs are 3€/MWh, so that in both periods he earns 3,5€ (=3,5€/MWh*1MWh), which is enough to compensate for his fixed costs of 7€.
- Introduce a 2MWh block with a price limit of 4,75€/MWh.
- Etc.

In other words, generators using blocks have to fix volume to get revenue certainty. Therefore, generators cannot directly express the costs and constraints by using blocks, which implies that the auction with blocks is not incentive compatible for generators. However, blocks can also be introduced at the demand side. Therefore,

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[16] One of both proposals for the creation of the California Power Exchange was a multi-round auction with activity rules.

also consumers can express their multi-period cost structures. For instance, a block can be introduced for the start-up of an energy-intensive production process.

As with multi-part orders, a market-clearing price does not necessarily exist for an auction with block orders. Instead of resorting to nonlinear pricing, European exchanges (also Omel) impose linear prices[17]. These prices are not necessarily market clearing, i.e. block orders can be excluded even though they are in the money. In other words, blocks that want to trade as they can make a profit at the determined prices can be rejected without receiving a compensation for the lost opportunity. In this text, these blocks are referred to as Paradoxically Rejected Blocks (PRB).

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[17] European power exchanges therefore fit the definition of Stoft (2002) of a power exchange. For him an exchange is a centralized market not making side payments, even if it uses blocks or multi-part bids.

2.3 Standard market design

In the US, the standard market design supported by the Federal Energy Regulatory Commission (FERC) is basically the PJM design, its most successful market[18]. Therefore, the standard market design advocated in the US is a system with a mandatory pool, multi-part bidding and nonlinear and nodal pricing. While there is no standard market design in Europe, it is possible, using the discussion in the previous sections, to advance a prevailing design[19]:

- Trading arrangements are not pool based but bilateral.
- The exchanges only have block bidding (less flexible than multi-part bidding in pools) and apply linear pricing instead of nonlinear pricing.
- At the moment, most exchanges organize trade nationally so that they do not take into account network constraints and arbitrage between the zones is via separate capacity markets.

At first sight, these designs seem very different. However, Europe is moving towards a system with implicit allocation of network capacity. There is still a zonal system in place but full spatial arbitrage as in a nodal system may be too much to ask for. The arguments for simplification are that there are few agents at each node, which makes the market illiquid. It may not make much sense to have as many prices as the number of physical nodes in a network. As in Nord Pool, control zones could gradual split in several price zones. In other words, the designs are actually not that different.

It is also increasingly recognized that electricity markets are too complex to be modeled adequately so that there will never be closure on best design. Illustrative is the statement by Newbery (2005) as one of the conclusions in the framework of the SESSA project for the European Commission on refining market design: *"The British evidence of increased wholesale competition suggests that, where the market design is reasonably sensible, market structure is determinative."*

Bushnell (2004) noted that, ironically, in response to its crisis, California is moving to adopt a market design somewhat similar to the UK Pool[20], which has in turn been rejected in the UK in favor of a design similar to the one that has now been rejected in California. The following two sections describe the events and provide a sample of relevant literature.

2.3.1 UK experience

The UK Pool, actually the Electricity Pool of England and Wales, was introduced as part of the liberalization process that started in 1990. Scotland and Northern Ireland

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[18] Note that it is successful in terms of short-run allocation. In terms of long-term investment, this market has still to deserve its merits.

[19] See Glachant et al. (2005) for a detailed discussion of market design issues that need to be improved in Europe.

[20] More specifically California is moving towards the FERC's standard market design, which is basically the PJM Pool system.

were subject to separate market arrangements, which will not be further discussed. The Pool operated for 10 years until it was subjected to a review process. Following this review by the regulator Ofgem, at that time called Offer[21], the Pool was replaced with the New Electricity Trading Arrangements (NETA) in 2001. NETA basically implied that a bilateral trade based market with PXs[22] replaced the pool-based market architecture. A more comprehensive discussion of the liberalization of the UK market and its transition is provided by Bartholomew (2004).

As stated in Bower and Bunn (2000), the review was part of a wider UK energy policy debate, with

- Consumer groups, who believed that the Pool contributed to generator market power and high prices.
- Offer, who wanted to create a more competitive industry and greater synergy with the gas market. Illustrative is the explicit statement "Pool prices must come down" by the regulator (Offer, 1999).
- The government, which was concerned about fuel diversity and security, wanted to prevent excessive investments in gas-fired generation capacity at the expense of coal.

Most parties believed that the defaults of the Pool could be remedied by redesigning the Pool. Often cited was that both the marginal system price and the capacity payments calculation methodology provided opportunity for generators to profit from market manipulation. Most suggested remedies were therefore simplifying price rules[23], discriminatory pricing and the abolishment of the capacity payments.

Neushloss and Wolf (1999) and many others state that perhaps the most important reason for the abolishment of the Pool was the governance arrangement that created a deadlock situation. Changes to trading rules could only be implemented with the consent of a majority of Pool Members. Furthermore, the voting system was weighted in favor of larger participants.

Ofgem has credited the fall in electricity prices in England and Wales after the introduction of NETA to the new market design. This as well is however controversial. Empirical analysis by Evans and Green (2002) supports this view, while Bower (2002) and Newbery (2003) argue that the decline in price is fully explained by the reduction in market concentration brought about by asset divestitures, an increase in imports and market excess capacity. Fabra and Toro (2003) on the other hand, suggest that besides the reduction in market concentration,

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[21] Started with: Review of Electricity Trading Arrangements - A consultation Paper, Offer, November 1997, after which many documents followed, most are available at: http://www.ofgem.gov.uk.

[22] This led to the creation of several exchanges, the most important one being UKPX. Note that UKPX is the only exchange in Europe that does not organize an auction but facilitates continuous trade in half hourly contracts up to 2 hours before delivery.

[23] Offer identified in its review that the Pool is overly complex, for example, it requires the submission of at least nine different order parameters for each generator set and requires a rulebook, of over six hundred pages, to describe the price calculation methodology.

the change in market design is significant in explaining the reduction in wholesale electricity prices.

2.3.2 California experience

When restructuring of the electricity industry in California started in 1996, the state was facing some of the highest retail rates in the US. The California Public Utilities Commission (CUPC) decided to provide supplier choice, at first only to large consumers, later also to all retail customers. The FERC had already started promoting wholesale electricity markets throughout the US. In contrast with the UK Pool, the California PX (CalPX) was not a mandatory market, but intended to compete for trading volume with other markets. There was however a significant liquidity supporting measure: California's three main suppliers Pacific Gas and Electric (PG&E), Southern California Edison (SCE) and San Diego Gas and Electric (SDG&E) had to utilize the PX and the California ISO real-time market for their wholesale electric energy needs.

Figure 2-3 shows that starting May 2000 energy prices climbed to previously unseen levels, averaging at 110$/MWh that year. The Figure is taken from Borenstein et al. (2002) who investigated market power abuse, which they measure as a margin over an estimated perfectly competitive price (dashed line). Their study indicates that there were already signs of future trouble as early as August 1998, the critical difference being that imports were lower and costs were higher in 2000.

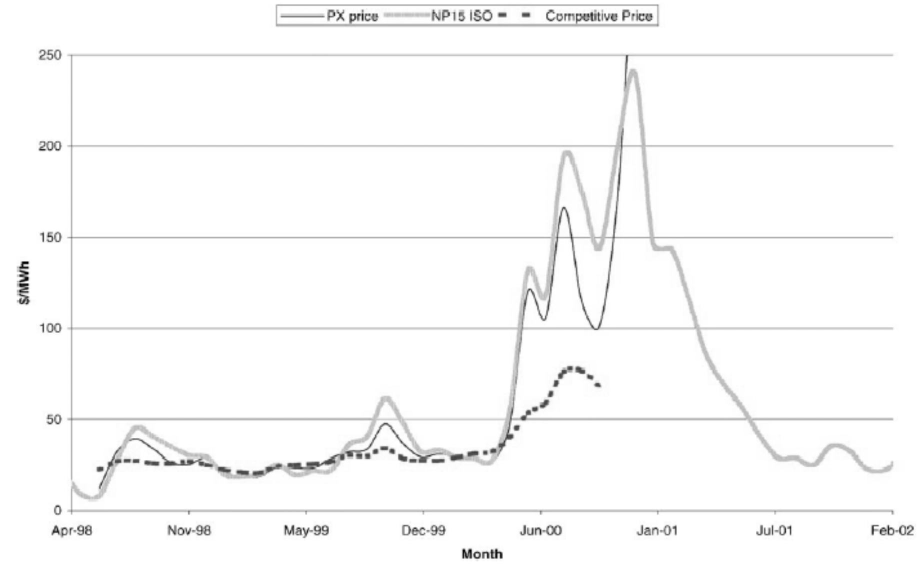

Figure 2-3: California electricity prices Borenstein et al. (2002)

As discussed in Bushnell (2004), there was a retail freeze at a level equivalent to about 60$/MWh, meaning that in 2000 they lost about 50$/MWh for each MWh they carried to their customers. In 2001, California's largest utility PG&E declared bankruptcy and SCE came close to declaring it. Generation companies that were no longer paid for their output began to shut down their facilities. Rolling blackouts occurred in January, March and May 2001. Bushnell (2004) argues that the financial stress of the utilities created the physical supply crisis, although there were also many accusations of 'withholding' during the rolling blackout period.

Many observers underlined the regulatory failure. An in depth discussion of the market rules and regulations is provided in Wolak (2003) and in Peterson and Augustine (2003). Perhaps most striking is the reaction of the FERC after the price surges in the summer of 2000. The FERC eliminated the requirement for the utilities to use the PX and the California ISO real-time market for their wholesale electric energy needs, which lead to the bankruptcy of CalPX in the beginning of 2001. The FERC also proposed replacing the 250 $/MWh hard price cap in both markets by a soft cap of 150 $/MWh. This soft price cap required all generators to justify bids in excess of 150 $/MWh. In 2001, the Market Surveillance Committee noted that the average real-time wholesale energy price during Jan 2001 was approximately 290 $/MWh despite the existence of a 150 $/MWh soft cap. Many stated that affiliate transactions were used to raise the announced spot price of natural gas in California and thereby cost-justify higher electricity bids.

Others stressed that the only factor not seen in other markets in the world is the lack of contracts or other forms of long-term supply arrangements[24]. Given that the utilities had negotiated a retail rate freeze, one would think they would have had very strong incentives to hedge the wholesale price. Bushnell (2004) argues that there are two possible reasons why they did not. One is that they simply did not believe spot prices could possibly exceed the levels set in their retail rate freeze. The other possible explanation is that the utilities expected that the retail freeze was not firm. However, the appeal of PG&E and SCE to raise retail rates to reflect the dramatic increase in wholesale prices after the summer of 2000, was refused by CPUC.

From the beginning of 2001, the state of California started signing long-term contracts with durations averaging approximately 10 years. Most of these contracts began delivering in the summer of 2001. By the summer of 2001 spot prices returned to pre-crisis levels, as illustrated by the shaded line in Fig 1, which depicts the real-time prices in the ISO market.

2.4 Appendix

Determining the efficient dispatch in the example in section 2.2.3.1 implies solving a unit commitment problem. This means maximizing gross demand surplus minus the cost of supply, subject to the constraint of the sellers:

$$\max_{q^D, q^S} \int_0^{q^D} P(q) q dq - \sum_{j=1}^{4} (v_j q_j^S + f_j z_j) \tag{2.1}$$

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[24] Some models of endogenous forward contract prices indicate that forward markets reduce market power (Allaz and Vila, 1993). However, this is disputed by others (Harvey and Hogan, 2000). For instance Spain, also a highly concentrated market, has used long term contracts to restrain the incentives of market parties to bid much above costs (Crampes and Fabra, 2005).

Subject to:

$$q_j^S - K_j z_j \leq 0 \tag{2.2}$$

$$q^D - \sum_{j=1}^{4} q_j^S = 0 \tag{2.3}$$

$$q_j^S, q^D \geq 0 \tag{2.4}$$

$$z_j \in \{0,1\} \tag{2.5}$$

With:

- q_j^S the production and q^D the optimal level
- $j = 1,...4$ the sellers
- v_j, f_j the variable and fixed start-up costs of the seller (Table 2-2)
- z_j a binary variable that is 1 if the seller supplies (2.2)
- K_j the maximum capacity of the seller (Table 2-2)

2.5 Conclusions

The contribution of this chapter is to put the design of European power exchanges in perspective. The conclusion is that auctions organized by power exchanges in Europe are different from auctions elsewhere.

They have in common with power pools that they take into account non-convexities. However, the way they do this is very different. First, the exchanges have block orders instead of the multi-part orders. In contrast to an auction with multi-part orders (pool), an auction with block orders (exchange) is not incentive compatible for generators. However, blocks can also be introduced on the demand side and therefore also allow consumers to express their multi-period cost structures. Furthermore, the use of blocks is so common in Europe that it will be taken as given in the remaining of this text.

Second, the exchanges do not actually clear their auctions. They impose linear prices and blocks can become 'paradoxically rejected'. In chapters 5 to 8 this approach is further analyzed. Important for that analysis is that exchanges are voluntary markets. It means that inefficient trade in these auctions does not necessarily lead to inefficient wholesale trade and inefficient dispatch, as there are many trading alternatives.

Third, the exchanges do not take into account network constraints, with the exception of Nord Pool. However, Europe is moving towards a system with implicit allocation of network capacity, meaning that the treatment of international transmission constraints is also relevant for exchanges.

Finally, different market design standards take shape in Europe and the US, which can be partly explained by different experiences. The difference in design should however not be exaggerated, as Europe is actually moving towards a more centralized design.

Chapter 3

Laboratory on the competitive functioning of the European Electricity Market

3.1 Introduction

As discussed in the previous section, auction rules do not always allow traders to express their costs. However, if the auction design allows them to express their costs, this does not necessarily mean they will. This chapter illustrates such cost deviating behavior in a simplified laboratory setting.

This chapter discusses the Leuven Electricity Spot Market Game (LESMAG), an educational tool for the integrated European electricity market, and reports the usage of the tool as part of a course in Power Economics.

LESMAG models an integrated European power market. It takes into account not only the technical issues, modeling the production park of the generation firms and the transmission network, but also the economic aspect, modeling the bidding, and market clearing process, and the resulting profit for the firms.

LESMAG can be used to teach power economics to engineering students, to explain economists the effect of congestion on market clearing, and to train traders in their bidding strategies.

The goal of the laboratory is that students gain some insight into cost deviating bidding behavior of generation firms. Students play the role of generation firms that offer to supply electric energy in a mandatory auction. Abstraction is made of non-convexities and multi-part bidding (see chapter 2) so that the focus is on the effect transmission constraints have on their competitive behavior.

Others have reported successful experiences with electricity games without network constraints (Debs et al., 2001; Anders, 2000; Kumar and Sheble, 1998; Contreras et al., 2001 and 2002). In this laboratory, these constraints are brought to the forefront, as they are an important barrier to competition in Europe (see chapter 1).

The laboratory[25] has been carried out two times at the KULeuven in Belgium, but also at Imperial College in London, UK, as part of a course on electricity markets for master students in electrical engineering. The chapter starts by explaining the game and ends with discussing the experiences with the laboratory.

3.2 Explanation of the game

In this section, respectively a general description of the game is provided and its practical implementation.

3.2.1 Description of the game in general terms

The electricity game LESMAG simulates the European electricity wholesale market. It models the wholesale market in eight countries, the production park of the largest fourteen generation firms, and contains a simplified representation of the transmission network.

Generation firms own generation capacity in different countries, and submit bids for generating power in all the countries where they have production capacity. The players of the game submit bid functions.

3.2.1.1 Market clearing process of the auctioneer

The auctioneer clears the market subject to network constraints. Gains from trade are maximized, given the offers (t) received from the students (i) for delivery at different locations (z) and the demand bids (j) for consumption at location (z), which are fixed in the laboratory. Every order has a price and quantity limit (P, Q).

If there are no network constraints, it does not matter where the orders are introduced. It means that the accepted demand and supply quantities at a certain location can deviate freely, as long as demand equals supply totalized over all locations. If network constraints are taken into account, the difference between supply and demand at a certain location implies an injection in the network (if positive) or a withdrawal from the network (if negative) at that location. These injections and withdrawals or off-takes cause flows that have to be constrained in a limited capacity network.

The problem to be solved ((3.1)-(3.5)) can be formulated as follows, with the accepted order quantities (q_{izt}, q_{jz}) as the decision variables:

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[25] The laboratory is online accessible at: http://www.esat.kuleuven.ac.be/electa/teaching/ps.

$$\underset{q_{jz},q_{izt}}{Max}\left(\sum_{z}(\sum_{j}q_{jz}P_{jz}-\sum_{i}q_{izt}P_{izt})\right) \tag{3.1}$$

Subject to order constraints

$$q_{izt} \leq Q_{izt} \tag{3.2}$$

$$q_{jz} \leq Q_{jz} \tag{3.3}$$

and network constraints. There are two groups of physical constraints (laws of Kirchoff). First, the algebraic sum of injections and off-takes at each location and of the incoming or outgoing power flows must be zero. $\forall z$:

$$\sum_{i,t}q_{izt}-\sum_{j}q_{jz}-\sum_{x}B_{zx}(\theta_{z}-\theta_{x})=0 \tag{3.4}$$

With:

- B_{zx} susceptance of the line interconnecting zone z and x, given that ($x \in Z$)
- θ_{z} voltage angle

Second, the line capacities. $\forall z, x$:

$$B_{zx}(\theta_{z}-\theta_{x}) \leq Cap_{zx} \tag{3.5}$$

with:

- Cap_{zx} capacity of the line interconnecting location z and x

Note that (3.4) and (3.5) are the DC power flow constraints, which are a simplification of the real power flow equations as for instance discussed in Purchala et al. (2005). Furthermore, the voltage angles are often substituted in these constraints, which results in constraints with so-called flow factors or more specifically Power Transport Distribution Factors (PTDF).

This constrained optimization problem ((3.1)-(3.5)) is the so-called market-coupling problem or implicit auctioning problem. It can be solved with standard algorithms. The solution determines which orders to accept and at which locational prices the contracts are settled. The prices (pz) are the shadow or dual prices of (3.4).

3.2.1.2 Profit function of players and optimization method

When submitting their offers (P_{izt}, Q_{izt}), students maximize profits totalized over different locations, given a marginal function for every location $C_{iz}(q_{iz})$:

$$\underset{P_{izt},Q_{izt}}{Max}\left(\sum_{z}(p_{z}\sum_{t}q_{izt}-C_{iz}(q_{iz}))\right) \tag{3.6}$$

Subject to order constraints. First, at every location the student cannot offer to supply more than its maximum generating capacity at that location:

$$\sum_t Q_{izt} \leq Gencap_{iz} \tag{3.7}$$

Second, the student cannot offer to deliver at prices higher than the price cap. This price cap is a sufficiently large number, being 1000€/MWh in the laboratory:

$$0 \leq P_{izt} \leq \text{Pricecap} \tag{3.8}$$

Students also know the behavior of the auctioneer. They know how the auctioneer determines the accepted order quantities based on their orders and those introduced by others:

$$(q_{izt}, p_{izt}) = f(Q, P) \tag{3.9}$$

When submitting their orders, students do not know the orders submitted by their colleagues. Furthermore, the market result only yields aggregated information of the orders introduced by their colleagues.

3.2.2 Practical implementation[26]

The game encompasses Austria, Belgium, France, Germany, Italy, the Netherlands, Spain and Switzerland. There is only one node per country and all line impedances are assumed to be equal. The capacity values used for the internal interconnections of these countries are based on the NTC values (Box 1-7).

Students play the role of a generation firm and are randomly assigned one of the following firms: ACEA, AES, EDF, Edipower, Electrabel, EnBW, Endesa, Enel, E.ON, Essent, Iberdrola, Nuon, RWE and Vattenfall (Figure 3-1). The instructor is the market operator that organizes the mandatory auction where the generators compete to supply electric energy. In the following two sections, respectively the role of the students and the instructor are explained in more detail.

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[26] Thomas De Bontridder and Thomas Meersseman (2004) have implemented the first version of the auction model for their master thesis. Yulia Kallistratova has been so kind to implement the interface and the visualization of the market outcome (Figure 3-7) is based on code kindly provided by Konrad Purchala.

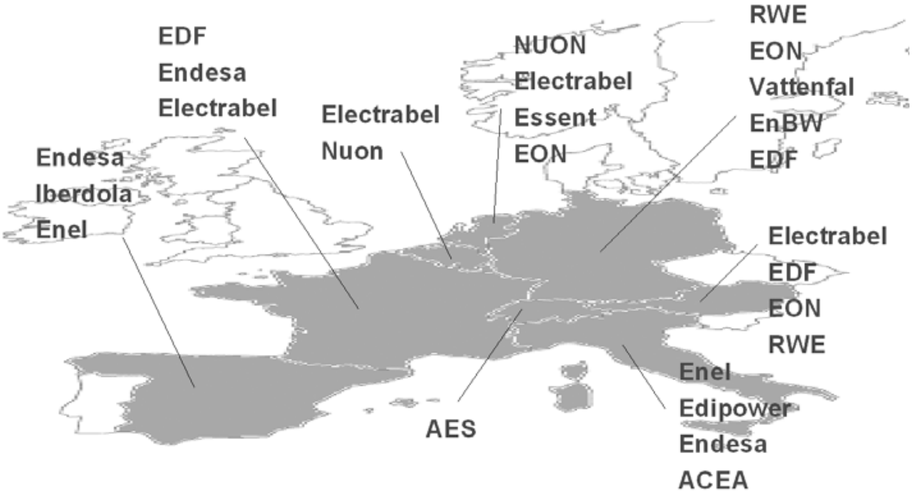


Figure 3-1: Generation firms and countries in the laboratory

3.2.2.1 Students

Students are a generation firm (i) that can supply in up to 3 countries (z). E.g. Iberdrola can only supply in Spain (Figure 3-2 illustrates the assumed marginal cost curve of Iberdrola in Spain ($C_{iz}(q_{iz})$). Iberdrola has a capacity of 16821MW ($Gencap_{iz}$), meaning that it can supply up to 16821MWh per hour. It is assumed that the generation firm can supply up to 8747MWh at a price of 0€/MWh. These marginal costs represent generation where variable costs are zero, e.g. wind and hydro generation. Those of higher supply levels represent the variable cost associated with gas and coal generation and the marginal costs of the highest level represent the variable costs associated with peak generation such as turbo jets.

In the game, a supply function is introduced by submitting up to 10 price-quantity pairs or orders (P_{izt}, Q_{izt}) at a certain location/country. E.g. if the student playing Iberdrola wants to introduce a supply curve equal to its marginal cost curve, he/she will introduce the following orders: (0,8747), (10,3028), (25,4542), (60,504). Note that this means that in total 16821MWh (8747+3028+4542+504) is offered, which is the maximum. Note also that the students actually have to submit the breakpoints of the supply curve (in this case (0,8747), (10,11775), (25,16317), (60,16821)) and that the operator derives these orders from that curve.

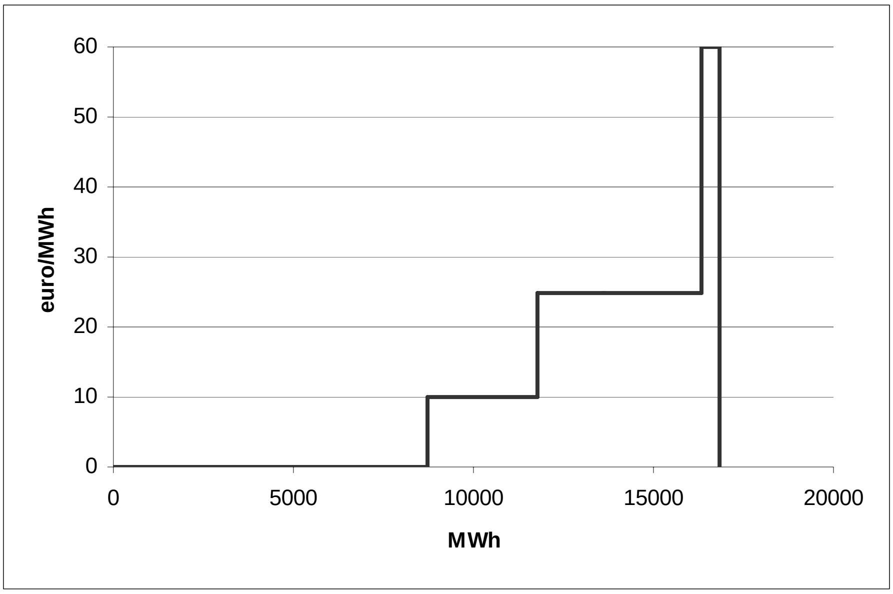
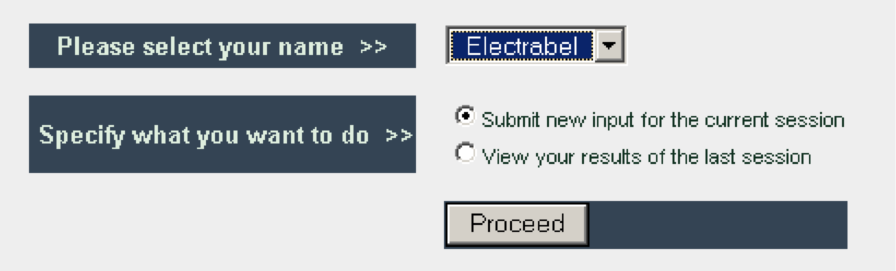


Figure 3-2: Assumed marginal costs of Iberdrola in the laboratory

When logged in, the student selects the generation firm he/she has been assigned to. Subsequently, he/she and can proceed to submit a supply curve or to view the results of the last session (Figure 3-3). Figure 3-4 illustrates the submission page of Electrabel. Several sessions are run so that students can learn from previous ones and can interact to improve their profits. Students are allowed to communicate during the game and can make agreements.

At the end of the laboratory, a spreadsheet shows the evolution of their performance (Figure 3-5). A work sheet is available per session with:

- The marginal cost curves already filled in (Figure 3-5: row 6-7 “Fuel costs”) for every country in which the student has to submit a supply curve (Figure 3-5 only illustrates Belgium).
- Room to fill in the breakpoints of the submitted supply curves (Figure 3-5: row 10-11). This curve is then visualized (Figure 3-5: "Bids" as opposed to “Marginal costs”).
- Room to fill in the market prices (Figure 3-5: row 14 “MCP”) and traded volumes (Figure 3-5: row 15 “traded volume”) afterwards as determined by the market operator.

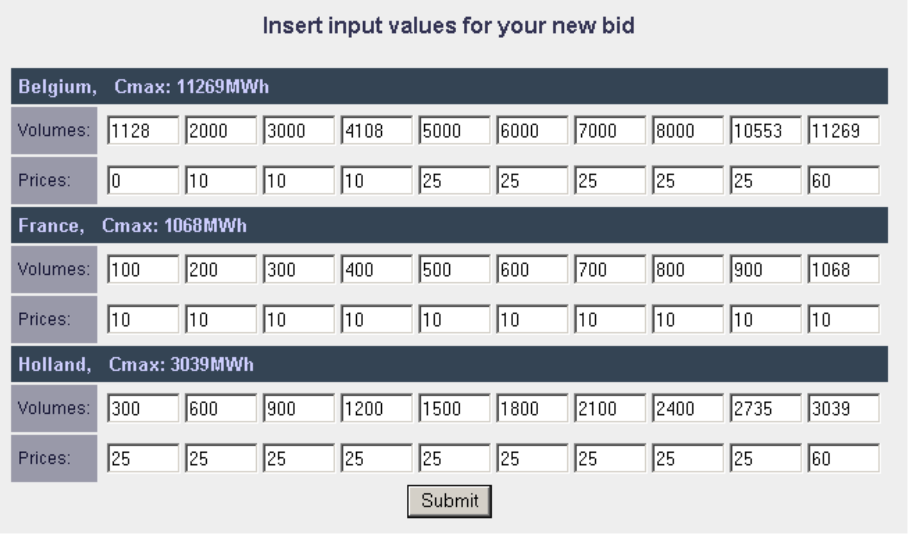


Please select your name >> Electrabel

Specify what you want to do >>

● Submit new input for the current session
○ View your results of the last session

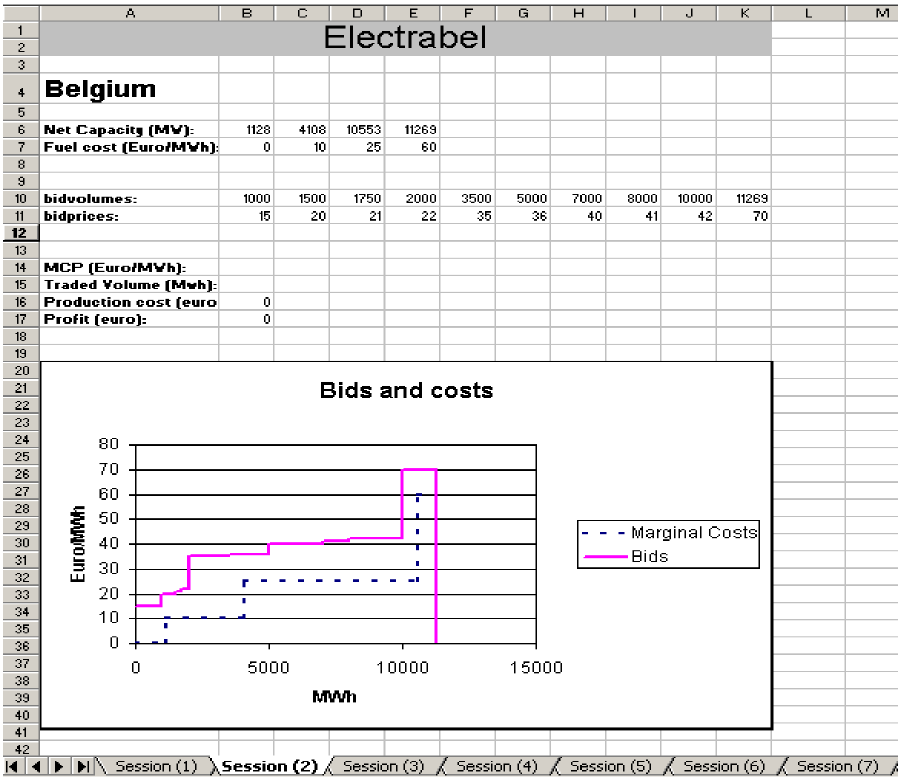
Figure 3-3: Student interface



Insert input values for your new bid

Belgium, Cmax: 11269MWh										
Volumes:	1128	2000	3000	4108	5000	6000	7000	8000	10553	11269
Prices:	0	10	10	10	25	25	25	25	25	60
France, Cmax: 1068MWh										
Volumes:	100	200	300	400	500	600	700	800	900	1068
Prices:	10	10	10	10	10	10	10	10	10	10
Holland, Cmax: 3039MWh										
Volumes:	300	600	900	1200	1500	1800	2100	2400	2735	3039
Prices:	25	25	25	25	25	25	25	25	25	60

Figure 3-4: Supply function submission page



Electrabel

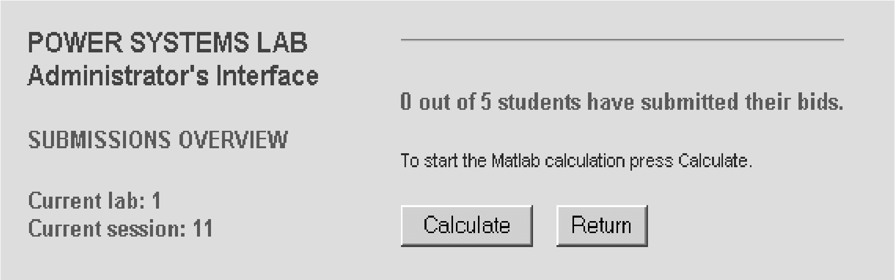
Belgium

A	B	C	D	E	F	G	H	I	J	K
Net Capacity (MV):	1128	4108	10553	11269						
Fuel cost (Euro/MVh):	0	10	25	60						
bidvolumes:	1000	1500	1750	2000	3500	5000	7000	8000	10000	11269
bidprices:	15	20	21	22	35	36	40	41	42	70
MCP (Euro/MVh):										
Traded Volume (Mvh):										
Production cost (euro	0									
Profit (euro):	0									

Figure 3-5: Spreadsheet

3.2.2.2 Instructor

The instructor is the auctioneer or market operator who receives the offers to supply from the students (Figure 3-6) and consequently closes that market and communicates the market outcome.



POWER SYSTEMS LAB
Administrator's Interface

SUBMISSIONS OVERVIEW

Current lab: 1
Current session: 11

0 out of 5 students have submitted their bids.

To start the Matlab calculation press Calculate.

Figure 3-6: Administrator interface

Every student privately receives his accepted or traded volumes per country and has access to the aggregated information. The aggregated information is made public as illustrated in Figure 3-7. Figure 3-7 illustrates a situation with congestion on the connections between France and Spain, France and Italy and France and Belgium (normally red line, now slightly darker line). As a result of these binding transmission constraints, there is no single price for the 8 countries, and prices vary from 10€/MWh in France to 48€/MWh in Italy. Under the prices, it is mentioned what is injected (+) in the network or withdrawn (-) from the network at per location. Next to the lines, the line loading (MW) is mentioned (white numbers).

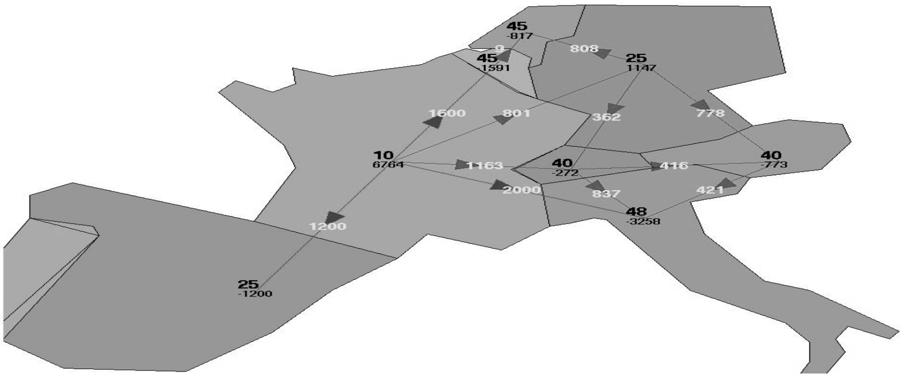


Figure 3-7: Visualization of the market outcome (competitive equilibrium)

Additionally, students have access to the aggregated curves of every country. The aggregated supply curve is an aggregation of the supply curves submitted by all generation firms active in a country. Figure 3-8 illustrates this for the Netherlands in a certain session, where the generation firms Electrabel, EON, Essent and Nuon for the Netherlands are active.

In that session, the supply curve intersects with the demand curve at a price of 45€/MWh. At that price, demand and supply are equal (8750MWh). Note that demand is curtailed because the requested demand volume at 45€/MWh is actually 9500MWh. If supply is curtailed and different students offer to supply at the market price, their offers are curtailed proportionally to the requested volumes at the market price.

Without imports or exports, the price would be 45€/MWh in the Netherlands. The market operator however maximizes gains from trade totalized for the 8 countries, which implies in this illustration that the price in the Netherlands increases to 60€/MWh. At that price 8800MWh supply volume is cleared and 6500MWh demand volume. The difference (2300MWh) is exported.

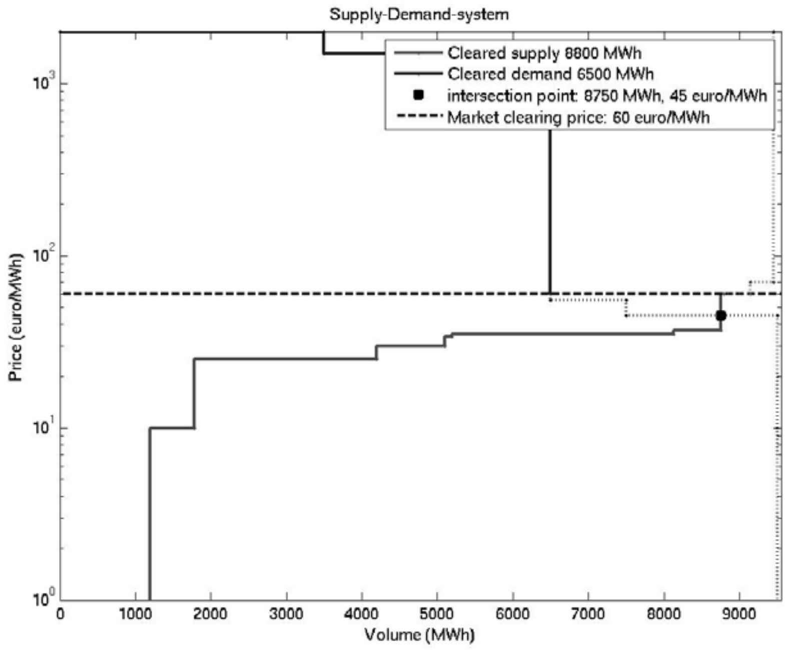


Figure 3-8: Market clearing at a location with export

3.3 Laboratory experiences[27]

In the first session of the laboratory, students are asked to submit their marginal costs. Figure 3-7 visualizes the market outcome of that session. It is explained to students that this is the solution under perfect competition and that they should try to improve their profits by interacting with each other. The Excel sheet that keeps track of their performance throughout the laboratory sessions benchmarks that performance against the profits under perfect competition.

Electrical engineering students are not always familiar with the concept of market power, i.e. the ability to profitably control prices. In the three laboratories that have been organized, students were very prudent and did not easily raise their supply curves significant above marginal costs. In the laboratory illustrated in Figure 3-9, prices in Spain increased significantly from session 1 to 5 without any intervention of the instructor, reaching up to 160€/MWh in session 5.

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[27] Thomas Meersseman, Leen Vandezande and Karolien Verhaegen have been so kind to help organizing these laboratories for students.

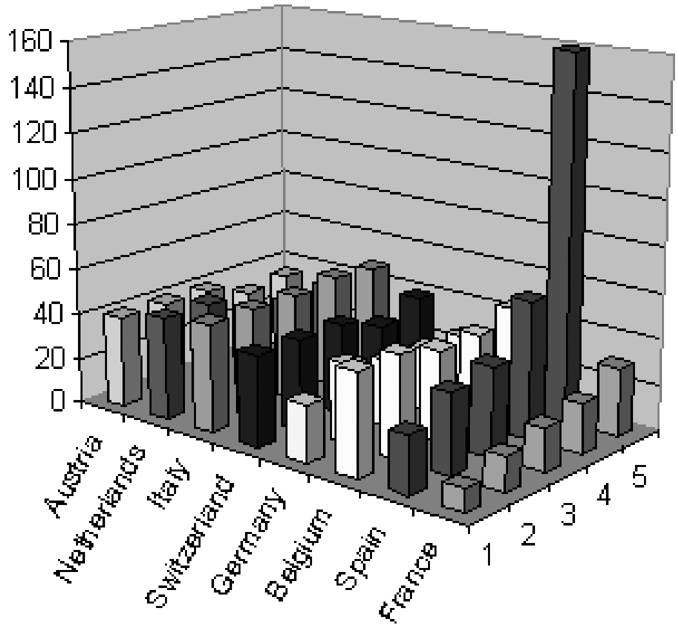

Figure 3-9: Locational price evolution from session 1 to 5

Table 3-1 illustrates that there are two dominant players in Spain, being Iberdrola and Endesa. Even though the interconnector is not generating capacity as such, it reflects the import potential of Spain and should therefore be taken into account when analyzing their competitive behavior. The sum of the capacities of the interconnectors is actually an upper bound of the import potential. Especially for markets as France, the import (or export) potential is lower than the total interconnection capacity as the power flows are not distributed over the different lines according to capacity but according to the impedances.

Table 3-1: Generation and interconnection capacities in Spain

Endesa	45%
Iberdrola	46%
Enel	6%
Interconnector	3%

In the laboratory, Iberdrola and Endesa therefore have 91% of Spain's supply capacity (Table 3-1). High concentration in combination with high demand and a low demand elasticity can imply that these players have market power, meaning that they can increase their profits by supplying less as this yields much higher prices.

Figure 3-10 shows that the student playing Iberdrola indeed lifted its supply curve gradually from session 1 to 4 with a substantial shift upwards in session 5. As illustrated in Figure 3-11, this strategy increased the student's profits with a factor 10 from session 1 to 5. Figure 3-11 also shows that Endesa's profits increased even more than the profits of Iberdrola. This is because the volume supplied by Endessa increased, while the volume supplied by Iberdrola decreased as a consequence of its strategy (Figure 3-12). However, this is not necessarily so as it also depends on other parameters such as the marginal costs, etc.

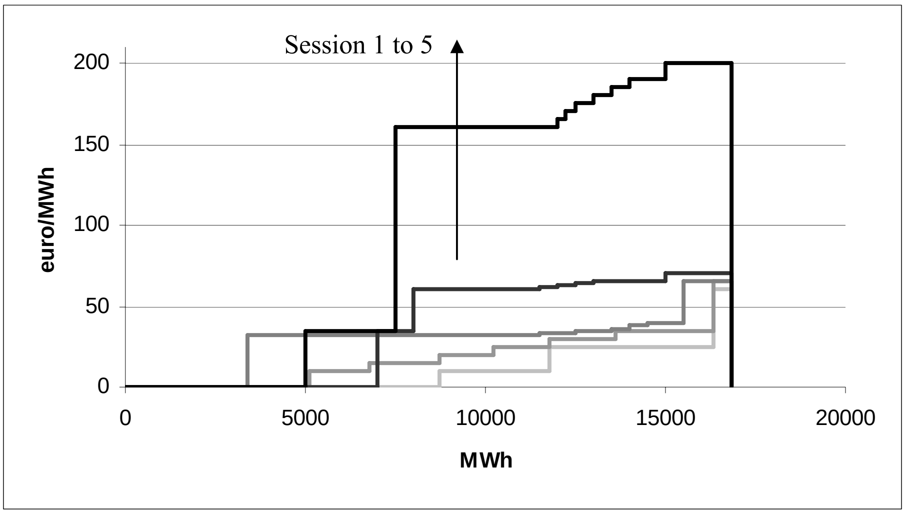

Figure 3-10: Supply curves submitted by student playing Iberdrola

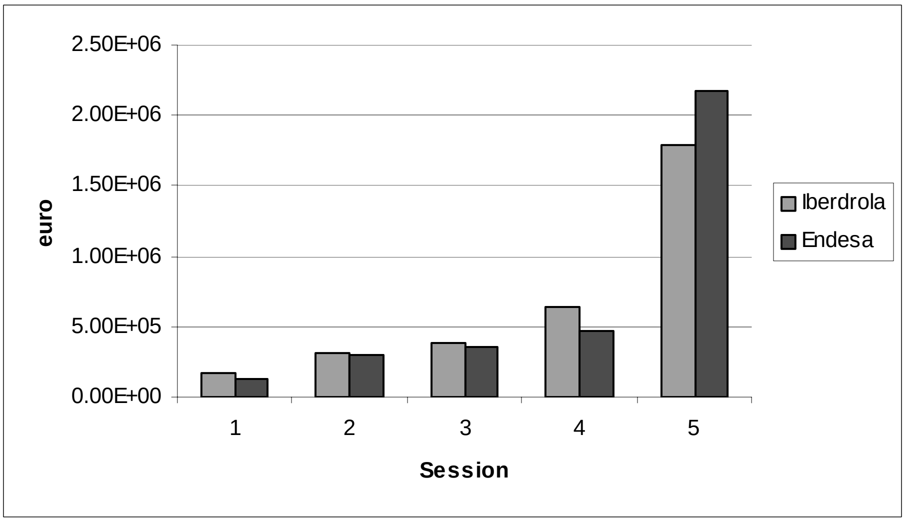

Figure 3-11: Profit Iberdrola and Endesa in Spain

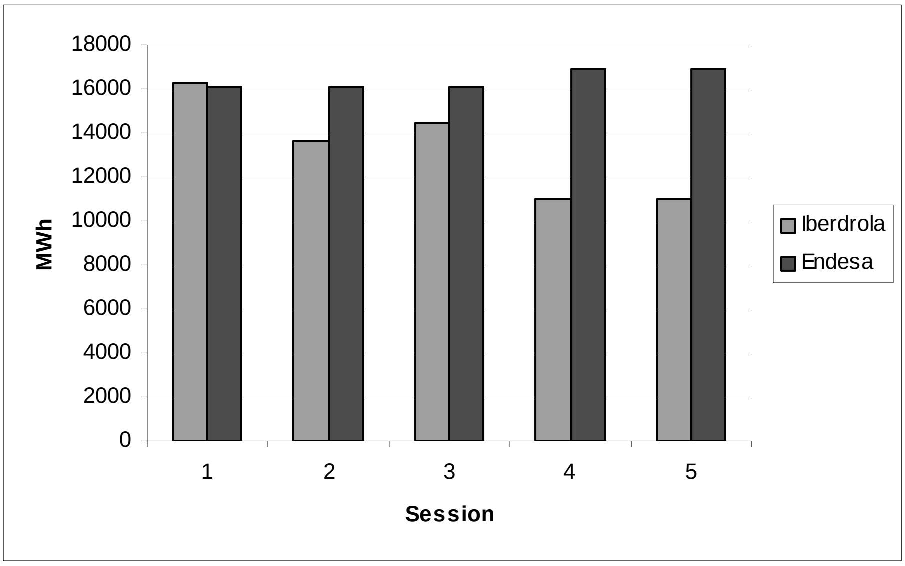

Figure 3-12: Accepted volume Iberdrola and Endesa

As the laboratory progresses, students increasingly start to notice that they can exercise market power. Their behavior does however never fully converge to what could then be called the equilibrium solution of the laboratory. In the following section it is discussed whether such an equilibrium can be modeled.

3.4 Laboratory equilibrium

The actual game that is played should be modeled as a supply function equilibrium. These models are however computationally intractable, especially in combination with network constraints. For an overview of electricity market models and a discussion of supply function equilibrium literature, see Ventosa et al. (2005).

Cournot models are commonly applied to analyze electricity markets. These models assume that generation firms compete on quantities, instead of supply curves. In other words, the models do not completely represent the strategy space students have in the laboratory. Still, even Cournot models with network constraints are not without problems:

- As illustrated in Stoft (1999) and Cunningham (2002), an equilibrium does not necessarily exist and it is also possible to have multiple equilibriums. *Note that these findings are inline with the observation that the laboratory does not seem to converge to a solution*[28].

---

[28] The amount of noise in the laboratory should also not be underestimated as well. There can be human error, irrational behavior, students can interact and form cartels, etc.

- In the laboratory, students anticipate the behavior of the market operator. It is known to the students that the market operator optimally uses the network to maximize total gains from trade. As discussed in Hobbs and Helman (2004), Cournot models that take this into account are computationally intractable. To overcome this numerical problem, most studies assume that generating firms are naïve. For instance, it is implicitly assumed that generation firms do not anticipate that there can be congestion in the network.

3.5 Conclusions

The laboratory discussed in this chapter confronts students during several trading sessions with the interactions of their trading strategies. They are exposed to the functioning of the liberalized electric energy market and develop a feeling of the important role of the transmission network in this market.

The electricity industry is demanding an increasing number of electrical engineering students with knowledge of the competitive functioning of electricity markets. One way to develop this knowledge is by means of a game. This chapter described the experience with a laboratory developed for that purpose.

This chapter also introduced the market-coupling problem. The next chapter discusses the detailed implementation of the auction problem with network constraints. Chapter 9 discusses the market-coupling problem in the presence of blocks and political constraints.

For the argumentation in the next chapter it is important to note that supply offers seldom represent the actual marginal costs, as can be observed in experimental setting of the laboratory. Equivalently, demand bids seldom represent the actual willingness to pay. Furthermore, as discussed in this chapter, it is numerically infeasible to adequately model behavior in a simplified laboratory setting without block orders. Therefore, behavior of participants in not explicitly modeled in the remaining of this text that focuses on the treatment of block orders.

Chapter 4

Auction problem with network constraints

The previous chapter introduced the auction problem with network constraints and provided the optimization model. This problem has intensively been discussed in literature. In this chapter the well-known problem is applied to power exchanges, largely a European phenomenon.

Increasingly, the day-ahead auctions organized by exchanges are coupled to allow a better clearing of orders introduced at different countries. This implies that the exchanges take into account network constraints. Market coupling is implemented by solving the Linear Programming (LP) problem introduced in the previous chapter. Existing commercial software can then be used to solve the auction problem.

However, the LP problem does not uniquely determine prices and quantities. Due to verticals in the aggregated curves of the exchanges, there can be several price solutions to the auction problem. Furthermore, due to horizontals in the curves, there can be several quantity solutions. This implies that the software that is used to solve the problem has a significant impact on the determination of the market outcome, which is of course unacceptable. The contribution of this chapter is to discuss the problem and potential solutions. Respectively, indeterminacies in quantities and prices are discussed.

4.1 Problem applied to exchanges

In an international European context, market clearing with network constraints is referred to as market coupling. In Europe, it is about replacing the explicit allocation of cross-border capacities by a system where capacities are used to optimize the clearing of the orders introduced to the day-ahead auctions organized by exchanges.

Exchanges from different countries (z) receive hourly orders from the demand (P_{jz}, Q_{jz}) as well as the supply side (P_{iz}, Q_{iz}). As discussed in the previous chapter, given these orders and the network topology (B) and capacities (Cap), the market-coupling problem is as follows, with the accepted order quantities (q_{iz}, q_{jz}) as the decision variables:

$$\underset{q}{Max}\left(\sum_{z}(\sum_{j} q_{jz}P_{jz} - \sum_{i} q_{iz}P_{iz}) \right)$$

(3.10)

Subject to

$$q_{iz} \leq Q_{iz} \tag{3.11}$$

$$q_{jz} \leq Q_{jz} \tag{3.12}$$

$$\forall locations(z): \sum_{i} q_{iz} - \sum_{j} q_{jz} - \sum_{x} B_{zx}(\theta_z - \theta_x) = 0$$

(3.13)

$$\forall lines(zx): B_{zx}(\theta_z - \theta_x) \leq Cap_{zx}$$

(3.14)

The solution ($q_{iz}*, q_{jz}*$) determines which orders to accept of the different exchanges making optimal use of the available network. The shadow prices of (3.13) are then the market prices set for the auction participants.

4.2 Indeterminacies in quantities

Consider a simple single market example illustrated in Figure 4-1. Gain from trade is maximized at price p*, but from 100 to 150MWh can be cleared. In other words, solving this simple problem with (3.10) to (3.14) does not yield a unique solution in terms of quantities. In the illustration, the only choice is between more or less traded volume. As discussed in the previous chapter, the supply side does not necessarily represent the actual costs and the demand side not necessarily the real willingness to pay[29]. Therefore, in this example the solution that maximizes volume increases trade efficiency.

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[29] As discussed in the previous chapter, market parties can have an incentive to deviate their orders from costs in order to increase profits.

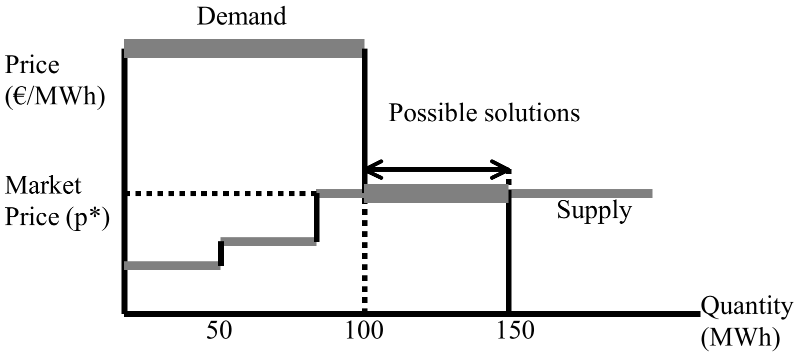

Figure 4-1: Single market example with horizontal intersection

Consider a simple multiple market example illustrated in Figure 4-2. Maximizing gain from trade fixes the total accepted volume (q*) and price (p*), but both locations have a supply order that is marginally accepted. If 50MWh is accepted of both orders, demand and supply are equal in both locations; otherwise there will be an unnecessary flow from one location to the other. Unnecessary flows should be avoided as they cause losses. Therefore, the solution that minimizes flow in this example increases trade efficiency. Note that losses are not taken into account in the market-coupling problem. As discussed in the previous chapter, the network constraints are based on DC flow assumptions and one of these assumptions is that there are no losses.

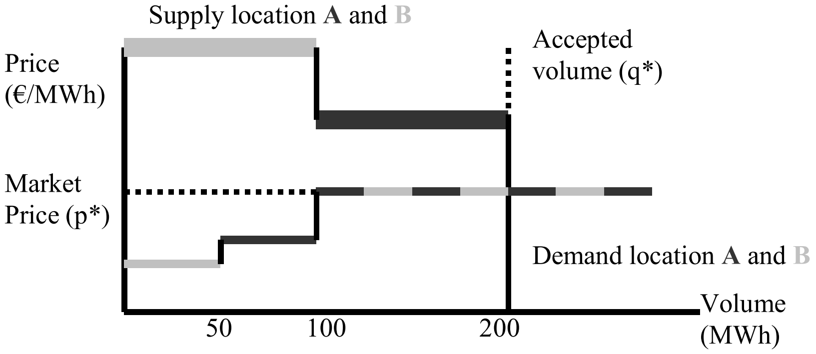

Figure 4-2: Two markets example with curtailed supply of different locations

In the above examples choosing between the different sets of solutions that maximize gain from trade is straightforward. However, consider the example illustrated in Figure 4-3. Gain from trade is maximized at price p*, but from 150 to 200MWh can be cleared:

- If the total accepted volume is 150MWh, demand equals supply in both locations A (50MWh) and B (150MWh) so that there is no flow on the line interconnecting these locations.
- If the total accepted volume is 200MWh, there is a 50MWh increase in demand and supply respectively in location A and B, meaning that 50MWh flows from B to A during that hour so that the load of the line is 50MW.

The choice between these solutions is not straightforward. More volume increases trade efficiency but also less flow and the exchange does not have adequate information to choose between the two. In other words, there is no clear answer to what practitioners should do. However, the above examples illustrate that besides gain from trade maximization, also traded volume and flow are necessary decision variables to determine a unique optimal set of accepted order quantities.

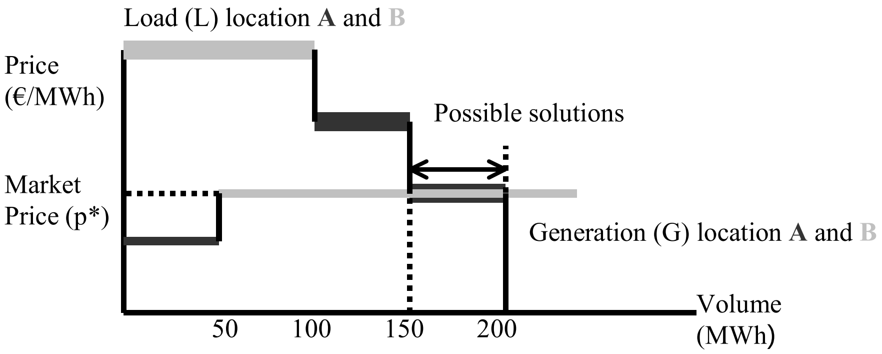

Figure 4-3: Two markets example: volume maximization or flow minimization?

4.3 Indeterminacies in prices

First, the price properties of the auction problem with network constraints are discussed. Second, it is explained and illustrated why the prices of this problem are sometimes not uniquely determined. Finally, potential solutions are discussed and an approach is proposed.

4.3.1 Price properties

Market coupling is also referred to as Locational Marginal Pricing (LMP)[30] because prices are determined as the shadow or dual price of the auction problem. Note that in optimization theory, the duality principle states that optimization problems may be viewed from either of two perspectives, the primal or the dual problem. In other words, the properties of LMP prices can be derived from the optimality conditions of the market-coupling problem.

---

[30] Note that the approach comes from Sweppe et al. (1998), where it is referred to as spot pricing of electricity.

The optimal solution to (3.10)-(3.14) is characterized by the existence of prices such that (3.15)-(3.17) hold, with p the dual prices of constraints (3.13) and μ the dual prices of constraints (3.14):

$$\forall locations(z): \frac{\partial\left(\sum_{z}(\sum_{j} q_{jz}P_{jz} - \sum_{i} q_{iz}P_{iz})\right)}{\partial q_z}(q_z) = p_z \tag{3.15}$$

$$\forall lines(zx): \sum_{x} B_{zx}\left[p_z - p_x + \mu_{zx} - \mu_{xz}\right] = 0 \tag{3.16}$$

$$\forall lines(zx): \mu_{zx}\left[B_{zx}(\theta_{zx} - \theta_{zx}) - Cap_{zx}\right] = 0 \tag{3.17}$$

(3.15) to (3.17) are the optimality conditions of the auction problem with network constraints. Equations (3.15) and (3.16) follow from the first order conditions of the Lagrangian[31] and Equation (3.17) is the complementary slackness condition. These optimality conditions can be translated as follows:

- (3.15) states that every location or market has a uniform price, i.e. all demand and supply orders are settled at the same price.
- (3.16) formulates the necessary relation between the prices.
- (3.17) states that a line that is not fully used has a zero price. If the line is fully used, it can but does not have to have a price different from zero, i.e. the price of a fully loaded line (μ_z) is undetermined.

As discussed in Stoft (2002), LMP is widely accepted as being able to provide the necessary incentives for an efficient short-term allocation of resources and long-term investments in electricity markets. However, LMP prices are not always as intuitive as one might think. Based on simplified examples in non-meshed networks, these prices have sometimes been attributed properties that the approach cannot deliver. Illustrative is the paper of Wu et al. (1996) on what these authors call 'folk theorems' of LMP. Furthermore, O'Neill et al. (2005b) discuss prices observed in PJM (applies LMP) that at first sight can be considered abnormal but are actually normal LMP prices.

It is for instance often thought that electric energy can only flow from locations with lower prices to locations with higher prices, i.e. there are no counter-flows. The following two sections, illustrate that this is the case for non-meshed networks, while it is not necessarily true for meshed[32] networks.

---

[31] $\Phi = \sum_{z}(\sum_{j} q_{jz}P_{jz} - \sum_{i} q_{iz}P_{iz}) + \sum_{z} p_z[\sum_{x} B_{zx}(\theta_z - \theta_x) - q_z] + \sum_{z}\sum_{x} \mu_{zx}[B_{zx}(\theta_z - \theta_x) - Cap_{zx}]$

[32] A network is meshed if there is more than one path between a combination of locations in the network.

4.3.1.1 Non-meshed network

Consider an example with 3 exchanges in a non-meshed network. Location 1 and 3 are connected with location 2 and there is no line between location 1 and 3. In that case, (3.16) simplifies into:

$$p_2 - p_1 = \mu_{12} - \mu_{21} \tag{3.18}$$

$$-p_1 + 2p_2 - p_3 - \mu_{12} + \mu_{23} + \mu_{21} - \mu_{32} = 0 \tag{3.19}$$

$$p_3 - p_2 = \mu_{23} - \mu_{32} \tag{3.20}$$

(3.18) and (3.20) illustrate for this example that the locational price difference always equates to the price of the line interconnecting these locations in a non-meshed network. Therefore, given that a line cannot be fully loaded in both directions at the same time and the price of a line cannot be negative it follows that a non-meshed network cannot have counter-flow.

4.3.1.2 Meshed network

As a simple example with counter-flows, consider 3 exchanges PX1, PX2 and PX3 to which the orders shown in Table 4-1 are introduced. Figure 4-4 illustrates the implied demand and supply curves at every location and how these locations are interconnected. All line susceptances are assumed to be one.

Table 4-1: Demand and supply at PX1-3 Example 1

PX1	PX2	PX3
Demand orders (bids)		
100MWh@ 90€/MWh	100MWh@ 90€/MWh	100MWh@ 90€/MWh
Supply orders (offers)		
200MWh@ 10€/MWh	200MWh@ 40€/MWh	200MWh@ 50€/MWh

Solving (3.10)-(3.14) yields the solution illustrated in Figure 4-4. The exchange with the highest price (PX3: 50€/MWh) is exporting and there is a counter flow between location 2 and 3, i.e. the flow is from PX1 to PX3, respectively the lowest (10€/MWh) and highest (50€/MWh) price location.

Without network constraints, the optimal solution is to accept the demand orders and to match demand (300MWh) with the supply orders of PX1 (200MWh) and PX2 (100MWh), meaning that 100 MWh is transferred from PX1 to PX3. A transfer between PX1 and PX3 reduces the cost of supply with 40€/MWh, which is the difference between the price limits of the supply orders at these locations. However, the network does not allow a large transfer between PX1 and PX3. All line susceptances are assumed to be one. Therefore, 2/3 of what is injected at location 3 and withdrawn at location 1 flows on the line between 1 and 3. Because this line has a very limited capacity of 10MW, only 15MWh can be exchanged between the lowest and highest price location.

Alternatively, gains from trade can be increased by transferring electric energy between PX1 and PX2, respectively the lowest (10€/MWh) and second highest price (30€/MWh[33]) location. Such a transfer reduces the cost of supply with 30€/MWh. Furthermore, only 1/3 of a transfer between PX1 and PX2 flows over the weakest line in the network so a transfer of 30MWh is possible, which is the double of the possible transfer between PX1 and PX3. In other words, more gains from trade can be created with a transfer between PX1 and PX2 in this network, i.e. 900€ (=30MWhx30€/MWh) instead of 600€ (=15MWhx40€/MWh).

A more counter-intuitive result is perhaps that PX3 is exporting. A transfer between PX3 and PX1 in itself indeed increases the cost of supply with 40€/MWh. However, 2/3 of this transfer creates a flow on the line between location 1 and 3 and this flow counters the flow caused by a transfer between PX1 and PX2. Therefore, a 2/3 capacity is freed on the weakest line. Furthermore, a transfer between PX1 and PX2 only uses 1/3 of this capacity so that 2MWh more can be transferred between these exchanges, which decreases the cost of supply with 30€/MWh. In other words, a transfer between PX3 and PX1 increases gain from trade in this network, i.e. 20€/MWh (=2MWhx30€/MWh-1MWhx40€/MWh).

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[33] Why this price is 30€/MWh and for instance not equal to the cost of supplying (as at the other locations), is explained in the next section.

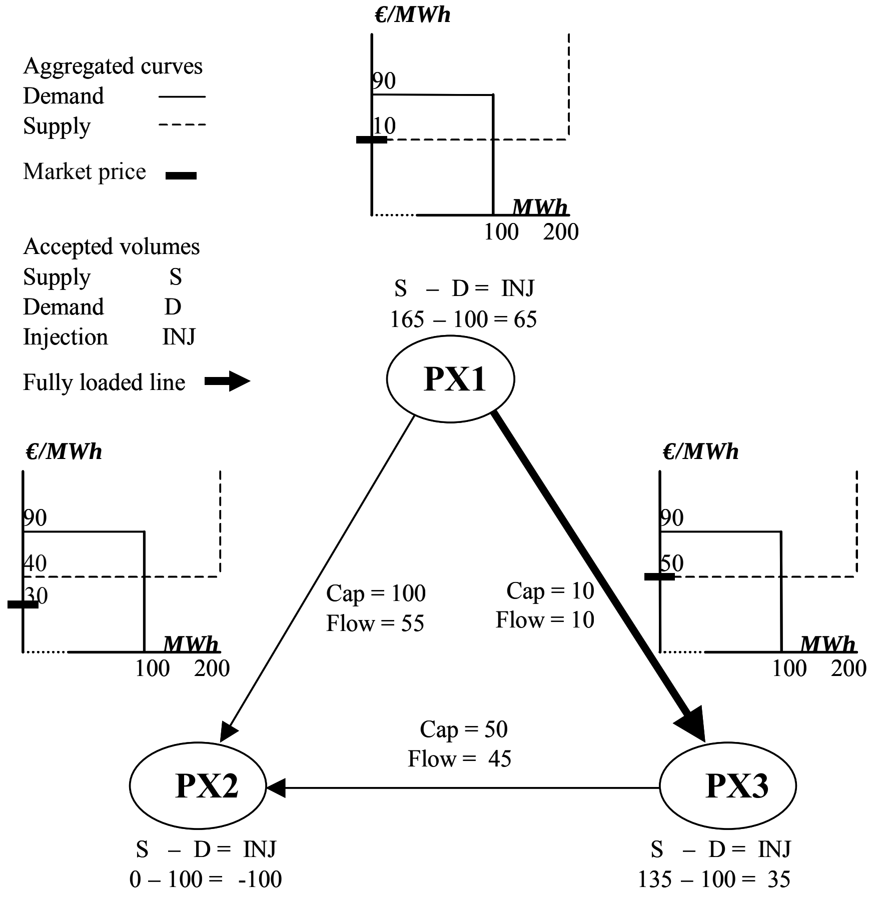

Figure 4-4: LMP 3 locations meshed with orders Example 1

4.3.2 Different price sets with the same properties

Indeterminacies in LMP prices exist if there is more than one price set that satisfies (3.15) to (3.17). First, it is explained how based on (3.15), price ranges can be defined. Then, it is illustrated that having price ranges does not necessarily mean that there are different sets of prices that satisfy (3.15) to (3.17). Finally, an example with several price sets is discussed.

4.3.2.1 Price ranges

As introduced in section 4.3.1, (3.15) only states that every location or market has a uniform price, i.e. demand and supply orders are settled at the same price. Demand and supply curves have verticals so that this condition in itself is not always sufficient to determine a unique set of prices. Sometimes this condition defines a price range. To explain how these price ranges are derived and how relevant they are, consider the following example summarized in Table 4-2 with two demand and supply orders submitted to the exchange for a certain period.

Table 4-2: demand and supply orders

Demand	Supply
100MWh@80€/MWh	50MWh@20€/MWh
20MWh@30€/MWh	100MWh@40€/MWh

In Figure 4-5, the orders are aggregated into supply and demand curves according to merit order. In the example, 100MWh can be cleared at 40€/MWh. In case the exchange is coupled to another exchange, the clearing can deviate from this intersection point of demand and supply, meaning that the exchange can export or import electric energy.

Figure 4-6 illustrates the locational price in function of what is exported or imported, i.e. net export curve:

- The exchange can export up to 50MWh at 40€/MWh, which equals the non-accepted volume of the curtailed supply order of 100MWh at 40€/MWh. If 50MWh is exported, this order is completely accepted, meaning that the price can also be higher than 40€/MWh. As long as the order is curtailed, the price has to be equal to 40€/MWh because a higher price implies a lost opportunity for the curtailed supplier.
- Up to 50MWh can be imported by further curtailing the supply order of 100MWh at 40€/MWh. If 50MWh is imported, this order is completely rejected, meaning that the price can also be lower than 40€/MWh. The price should at the same time be higher than 30€/MWh because the demand order of 20MWh at 30€/MWh is accepted.
- Etc.

In other words, the verticals of the net export curve are the price ranges. If the exchange level of an exchange is at such a vertical, (3.15) yield a price range equal to this vertical.

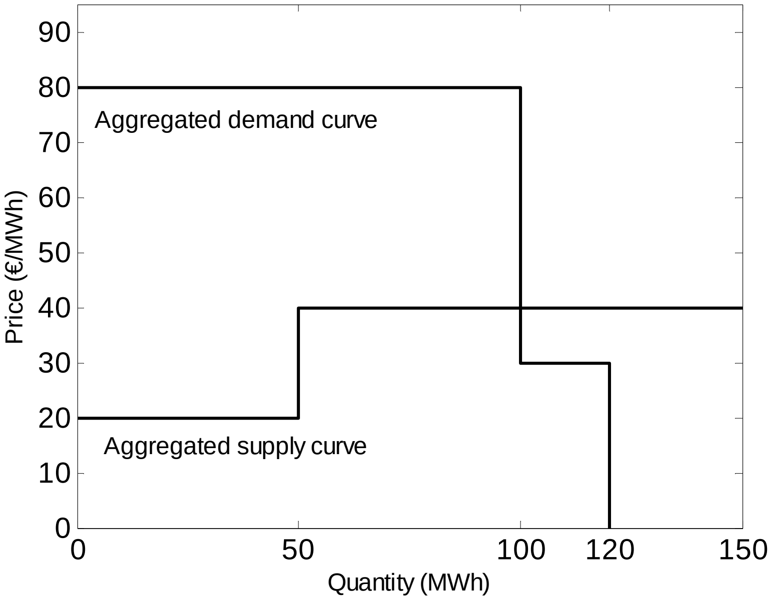

Figure 4-5: Aggregated demand and supply curve constructed from the orders in Table 4-2

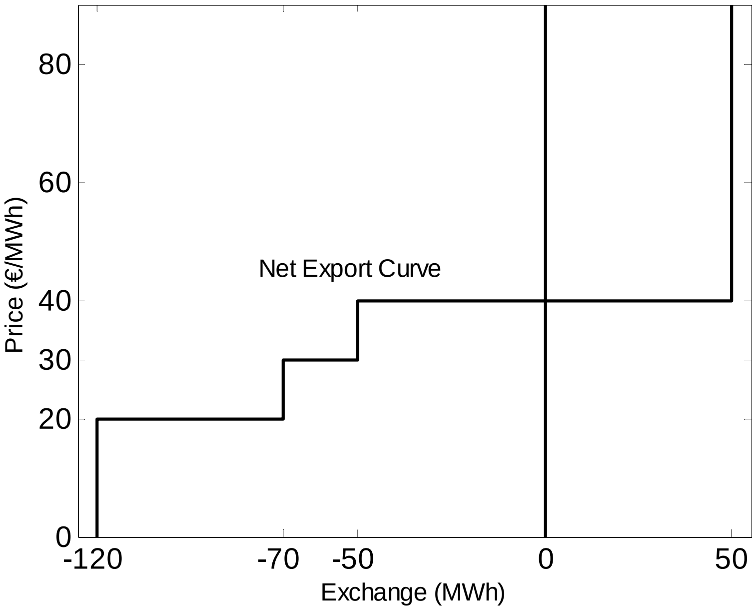

Figure 4-6: price range in function of export and import derived from the curves in Figure 4-5

The impact of how prices are determined on verticals, depends on the size of these verticals. APX publishes the aggregated curves on their website, e.g. Figure 4-7. Figure 4-8 illustrates that in January 2003[34] the verticals were 40€/MWh large on average and that 5% of these segments were larger than 200€/MWh. The size of the verticals is therefore not negligible, even though the largest segments are often at the end of the net export curve.

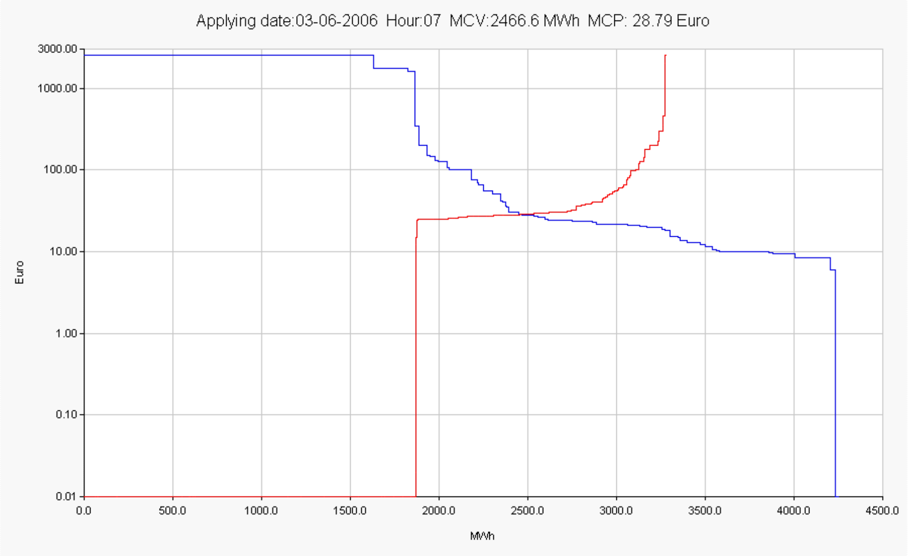

Figure 4-7: Aggregated curves example: APX (Netherlands) 07h 28-02-2006; 2444MWh cleared at 53€/MWh

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[34] Sample is taken from master thesis S. Cole (2005).

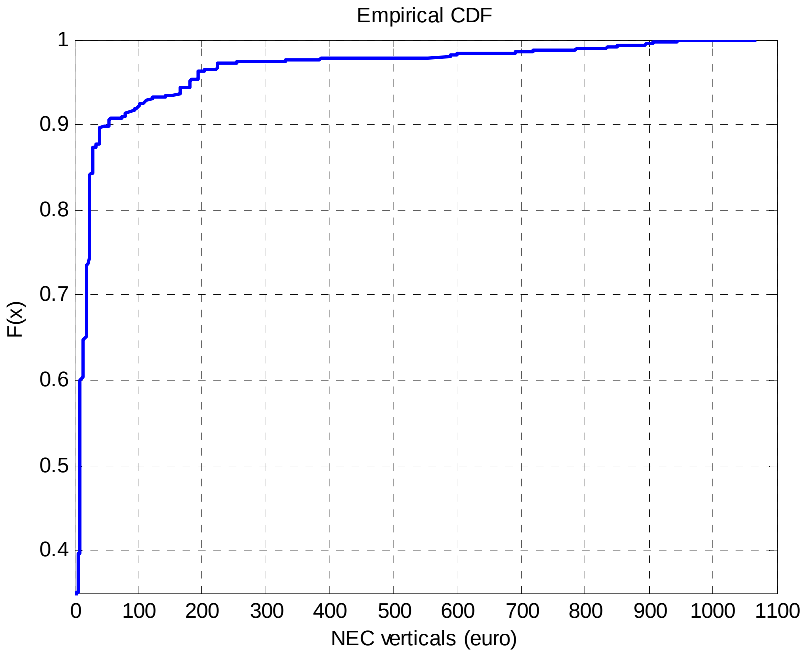

Figure 4-8: Cumulative Distribution Function (CDF) Size of verticals on NEC, e.g. APX January 2003

4.3.2.2 Price sets

4.3.2.2.1 Illustration with price range but single price set

In the example discussed in section 4.3.1.2, there is only one set of possible LMP prices (Figure 4-9). This is because the optimality conditions of the market-coupling problem determine a set of unique prices, which is explained as follows:

(3.15): only PX2 is cleared at a vertical in the net export curve, PX1 and PX3 do yield a price range. Therefore:

$$p_1 = 10, p_3 = 50, 0 \le p_2 \le 40 \tag{3.21}$$

(3.16): only the line between location 1 and 3 is fully loaded in the direction 1-3, the other two lines are not fully loaded. Therefore:

$$\mu_{12} / \mu_{21} / \mu_{23} / \mu_{32} / \mu_{31} = 0, \mu_{13} \ge 0 \tag{3.22}$$

(3.17) for this example yields:

$$2p_1 - p_2 - p_3 + \mu_{12} + \mu_{13} - \mu_{21} - \mu_{31} = 0 \tag{3.23}$$

$$-p_1 + 2p_2 - p_3 - \mu_{12} + \mu_{23} + \mu_{21} - \mu_{32} = 0 \tag{3.24}$$

$$-p_1 - p_2 + 2p_3 + \mu_{32} + \mu_{31} - \mu_{23} - \mu_{13} = 0 \tag{3.25}$$

Substituting (3.21) and (3.22) into (3.23)-(3.25) yields:

$$20 - p_2 - 50 + \mu_{13} = 0 \tag{3.26}$$

$$-10 - 2p_2 - 50 = 0 \tag{3.27}$$

$$-10 - p_2 + 100 - \mu_{13} = 0 \tag{3.28}$$

(3.26)-(3.28) is a set of two linear independent equations with two unknowns, meaning that prices are determined: $p_2 = 30$ and $\mu_{13} = 60$.

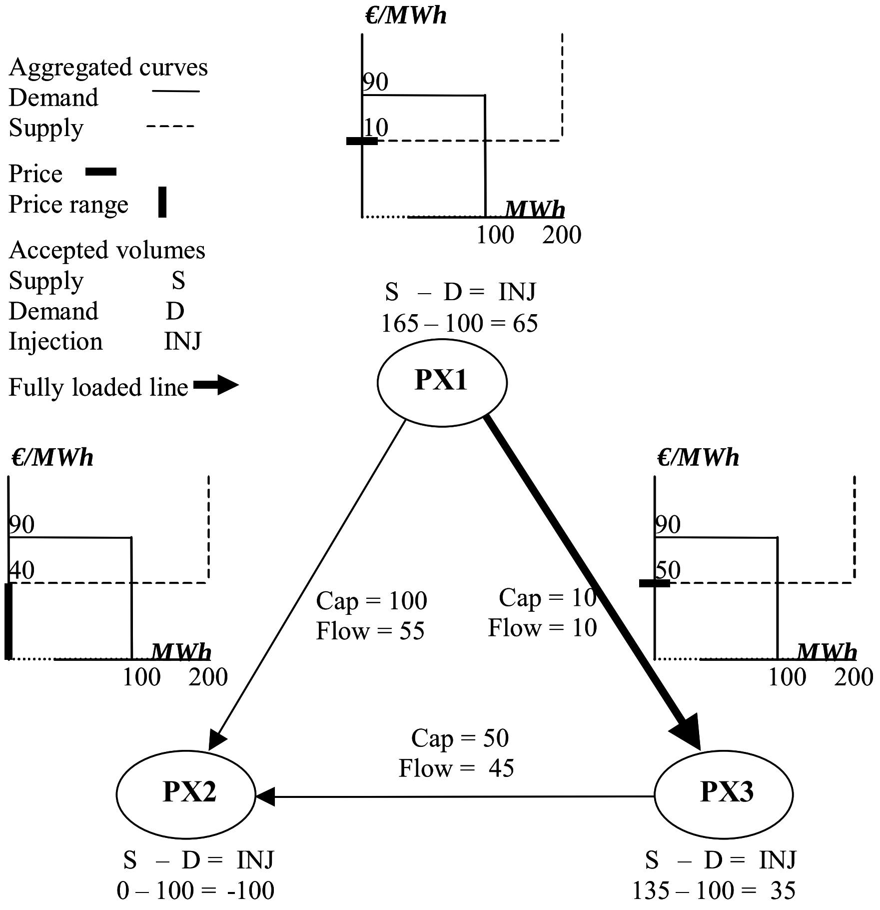

Figure 4-9: Example 1 yields a price range but only single price set

4.3.2.2.2 Illustration with several price sets

Consider 3 exchanges PX1, PX2 and PX3 to which the orders shown in Table 4-3, are introduced. Figure 4-10 illustrates the implied demand and supply curves in every location and how these locations are interconnected. All line susceptances are assumed to be one.

Table 4-3: Demand and supply at PX1-3 Example 2

PX1	PX2	PX3
Demand orders (bids)		
100MWh@ 90€/MWh	100MWh@ 90€/MWh	200MWh@ 90€/MWh
Supply orders (offers)		
300MWh@ 10€/MWh	150MW@ 30€/MWh	100MWh@ 50€/MWh

Figure 4-10 shows the optimal solution. The exchange (PX3) with the highest price is importing from the other two exchanges. Without network constraints, the optimal solution is to accept the demand orders and to match demand (400MWh) with the supply orders of PX1 (300MWh) and PX2 (100MWh), meaning that 200MWh is transferred from PX1 to PX3. The network does however not allow such a large transfer, i.e. maximally 50MWh can be transferred. Therefore, PX3 additionally imports 50MWh from PX2, the second cheapest price location.

The optimality conditions of the market-coupling problem (3.15) to (3.17) for this example yield:

$$30 \le p_2 \le 90 \tag{3.29}$$

$$50 \le p_3 \le 90 \tag{3.30}$$

$$20 - p_2 - p_3 + \mu_{13} = 0 \tag{3.31}$$

$$-10 + 2p_2 - p_3 = 0 \tag{3.32}$$

$$-10 - p_2 + 2p_3 - \mu_{13} = 0 \tag{3.33}$$

$$\mu_{23} \ge 0 \tag{3.34}$$

(3.31)-(3.33) is a set of 2 linear independent equations with 3 bounded unknowns so that prices are not uniquely determined, meaning that multiple price sets are possible. Indeed, solving the example in Matlab using the linprog solver yields prices of 10, 41,4 and 72,9€/MWh, respectively for PX1, PX2 and PX3 and solving it with CPLEX yields prices of 10, 30, 50€/MWh. In other words, the example clearly illustrates that prices can differ significantly depending on which software is used to solve the problem.

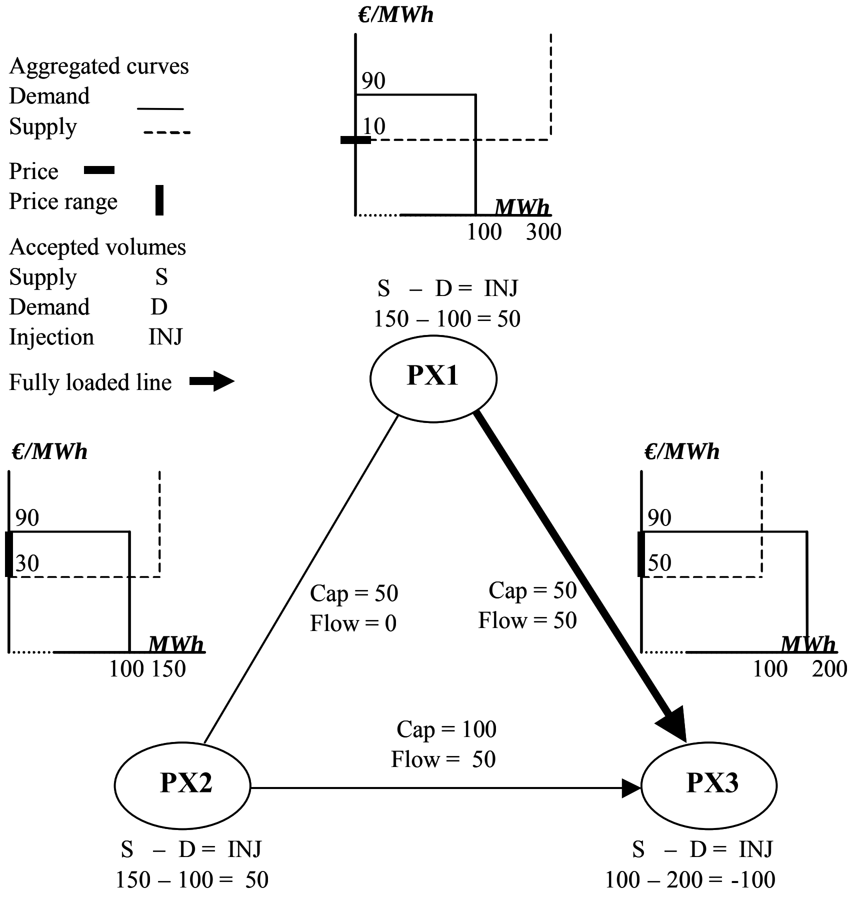

Figure 4-10: Example 2 yields two price ranges and several price sets

4.3.3 Choosing between possible price sets

Also in non-coupled exchanges the price can be undetermined on a range, i.e. when the demand and supply curve intersect vertically. Most exchanges then take the middle price. In Spain, Omel however selects the lowest possible price. Note that with the middle price more parties win.

The middle price rule applied by exchanges cannot be easily extended. This can be illustrated with Example 2 of the previous section. As there are two price ranges, there are two possible ways to start applying the middle price rule in this example:

- Taking p_2 at the middle of its price range (60€/MWh) means that from (3.32) follows that p_3 is 110€/MWh, which is conflicting with its price range and therefore not feasible.

- Taking p_3 at the middle of the price range (70€/MWh) means that from (3.32) follows that also p_2 is determined (40€/MWh), but not at the middle of its price range.

In the above example, it is not possible to take the middle price of both price ranges. It is only possible to take the middle price at location 3 and to determine the price at location 2 in function of this decision. In general, it is not neutral towards the different locations to take the middle price at one location and to determine the prices of the other locations in function of this arbitrary choice.

Prices should be determined by a global objective, which is neutral towards locations and therefore acceptable for all exchanges. Practitioners should then maximize this global objective, subject to (3.15) to (3.17), given the price ranges and the line loadings that result from solving the market-coupling problem (3.10)-(3.14).

Most global objectives are either discriminative towards the demand or supply side, such as maximizing or minimizing prices or demand or supply surplus. Alternatively congestion revenue could be minimized or maximized. Recall that the choice is between LMP price sets that yield equal efficient signals to demand and supply (as discussed in chapter 1: implicit auctioning). Note also that congestion revenue is a short-term cost for market parties that can be used in their long-term benefit via grid investment. However, as congestion revenue is not always used efficiently (Box 1-6), it can be argued that minimizing congestion revenue increases efficiency. Therefore, the proposed global objective is to minimize congestion revenue (CR):

$$\sum_z \left(\sum_j q_{jz} - \sum_i q_{iz}\right) \cdot p_z \tag{3.35}$$

When applied to the above example, the proposed approach (Min CR) implies solving the following LP problem:

$$Min(-50 \cdot 10 - 50 \cdot p_2 + 100 \cdot p_3) \tag{3.36}$$

Subject to (3.29)-(3.34)

Table 4-4 summarizes the sets of prices that respectively result from taking the shadow or dual prices given by linprog and CPLEX when solving (3.10)-(3.14) and the prices that result from Min CR.

Table 4-4: Different sets of LMP prices for Example 2

(€/MWh)	Linprog	CPLEX	Min CR	Max CR
PX1	10.0000	10	10	10
PX2	41.4413	30	30	50
PX3	72.8825	50	50	90

4.4 Conclusions

Market coupling is implemented as an auction problem with network constraints. The shadow or dual prices of this problem can then be used as market prices, i.e. Locational Marginal Pricing. Due to verticals in the demand and supply curves, there are in fact several sets of LMP prices. It has been illustrated that these verticals are not negligible in size. Furthermore, the simple rules as currently applied by exchanges to deal with verticals cannot be used for coupled exchanges.

An approach has been provided to consciously decide which LMP prices to take as market prices. It has been argued that a pricing approach that minimizes congestion revenue is the best alternative to using solver prices.

Less clear is how horizontals should be dealt with. As illustrated, both flow and traded volume, besides gains from trade, are necessary to uniquely determine quantities. It can be argued that both (more volume and less flow) increase trade efficiency, but how to weigh these objectives is arguable.

Chapter 5

Auction problem with blocks

The previous two chapters dealt with network constraints. As discussed in the introduction, most exchanges also have to deal with block orders. European power exchanges with block orders are APX (Netherlands), Powernext (France), EEX (Germany), EXAA (Austria), Borzen (Slovenia) and Nord Pool (Norway, Sweden, Denmark and Finland).

This part of the text bundles four chapters on the auction problem with blocks. This chapter introduces the problem and how exchanges deal with blocks. First block orders are introduced. Second, it is discussed how exchanges deal heuristically with blocks. Third, this approach is formalized as a constrained optimization model. Fourth, a batch of representative scenarios is introduced. Finally, the concept of Paradoxically Rejected Blocks (PRBs) is analyzed in detail.

5.1 Block orders

A block order consists of a quantity that is offered or requested in multiple hours at an average price limit. Besides this inter-temporal rigidity, blocks also have a fill-or-kill constraint, meaning that the order has to be accepted completely and in all hours included in the order, or not at all.

An auction with block orders could therefore be called a combinatorial auction. Combinatorial auctions are auctions in which participants can place orders on combinations of heterogeneous items, called packages or bundles, rather than just on individual items. An inspiring and comprehensive work on that topic is the book edited by Cramton, Shoham and Steinberg (2005). These auctions have recently been employed in a variety of industries. For example, they have been used for truckload transportation, bus routes, and industrial procurement, and have been proposed for airport arrival and departure slots, as well as for allocating radio spectrum for wireless communications services. De Vries en Vohra (2003) provide a survey on combinatorial auctions.

The advantage of combinatorial auctions is that participants can more fully express their preferences, such as complementarities between heterogeneous items. In electricity markets, there are complementarities between deliveries of electric energy in consecutive periods, for instance because of start-up costs of power plants (see chapter two: the costs of generators are non-convex). Block orders can indeed be seen as a combination of hourly orders. Instead of having to price the hourly orders separately, blocks allow participants to express an average price for a combination of hours. Therefore, blocks are characterized by a price and quantity, but also by the hours that are included in the order.

All exchanges restrict the size (MWh/h) or the type (span in terms of hours) or the amount (the number of blocks that can be submitted per participant per day times the number of participants) of blocks that can be introduced. Table 5-1 illustrates the 11 types of block contracts that can be traded on the German exchange EEX. On this exchange, blocks can be up to 250MWh/h in size. On other exchanges, the maximum size is more restricted. For instance, on the Dutch exchange APX the maximum block size is 50MWh. However, APX participants can submit more blocks per day, which suggests that there is some sort of trade-off that needs to be made. Block order restrictions (size, amount and type) are further discussed in chapter 7. With regard to this chapter, it is important to recognize that block order restrictions exist when constructing representative scenarios in section 1.1.

Important to note is that exchanges and participants consider blocks as important. Up to 20% of total traded volume on exchanges consists of block orders.

Table 5-1: Block products at EEX – auction market

Contract name	Time interval under block contract
EEX Night	Hours 1 to 6 (00.00-06.00 h)
EEX Morning	Hours 7 to 10 (06.00-10.00 h)
EEX High-Noon	Hours 11 to 14 (10.00-14.00 h)
EEX Afternoon	Hours 15 to 18 (14.00-18.00 h)
EEX Evening	Hours 19 to 24 (18.00-24.00 h)
EEX Rush Hour	Hours 17 to 20 (16.00-20.00 h)
Baseload	Hours 1 to 24 (00.00-24.00 h)
Peakload	Hours 9 to 20 (08.00-20.00 h)
Off-Peak 1	Hours 1 to 8 (00.00-08.00 h)
Off-Peak 2	Hours 21 to 24 (20.00-24.00 h)
Business	Hours 9 to 16 (08.00-16.00 h)

Note that almost all combinatorial auctions are single sided and that often participants can only bid on combinations of indivisible items. Power exchanges are therefore twice exceptional. First of all, they are double sided as blocks and hourly orders can be introduced at the demand side as well as at the supply side. Second, blocks (indivisible) are auctioned together with hourly orders (divisible). Therefore, power exchanges are an interesting reference market for combinatorial auction literature, but have not yet been described in this very recent literature.

5.2 Heuristic approach applied by exchanges

Exchanges only have a limited time frame available to solve the problem and publish results. They search for a good but not necessarily optimal combination of block orders to accept, i.e. specialized heuristic search. If N is the number of blocks in the problem, the number of combinations to be checked is 2^N. Given that exchanges easily deal with up to 100 blocks per day, the number of blocks to be checked is of the order of 1.3 E30.

Note also that to find the optimal solution it is not straightforward to eliminate combinations before checking them. Consider an example with three blocks A, B and C. It is not always possible to exclude ABC after checking AB. C can be a demand block, while A and B are supply blocks so that ABC is possible, while AB is not. Alternatively, A can be a demand block that cannot be accepted with supply block B, but can be accepted if also supply block C is added, etc. There are of course exceptions. For instance, consider two identical supply blocks A and B. If A is not possible, the same will count for AB.

The heuristic search algorithm is similar for all exchanges, but the details of the procedures are not publicly available. As described in Madlener and Kaufmann

(2002), all exchanges decompose the problem into a block selector and a coordination module that determines the price for a fixed block set.

Figure 5-1 summarizes the basic steps of the algorithm:

- The block selector selects a combination of blocks. The accepted blocks are transformed into price taking hourly orders, i.e. for every block an order is 'created' for every hour included in the block and with a zero price for supply blocks and the maximum price for demand blocks. The price taking hourly orders are added to the hourly orders.

- The determination of prices is then based on hourly orders. If no network constraints need to be taken into account, the hourly prices are at intersection of the aggregated supply and demand curves. Otherwise, an auction problem with network constraints needs to be solved, as discussed in the previous chapter. If these constraints are binding, prices can differ per location.

- The feasibility check at the end examines whether the average price constraints of the blocks that have been accepted are met. If the accepted supply blocks receive enough money and accepted demand blocks do not have to pay too much, a feasible combination of blocks has been found and the solution can be stored.

- The procedure stops when a time limit has been reached or when all combinations of blocks have been tried. The final solution is the best feasible solution that has been stored in terms of gains from trade.

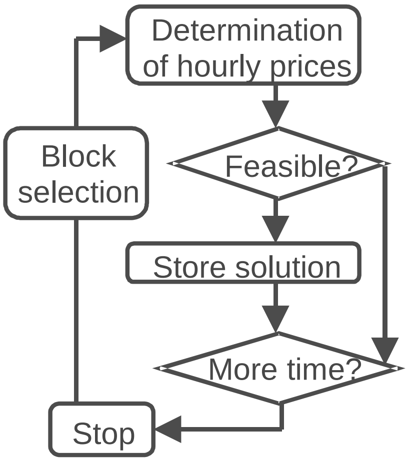

Figure 5-1: Heuristic procedure applied by European power exchanges to deal with blocks

As a simple example consider a 2-period auction with four simple hourly orders and one block order spanning both hours (Example 1: Table 5-2). There are two delivery periods (Pe1, Pe2): 100 MWh is requested at 90€/MWh in Pe1 and 150MWh at 90€/MWh in Pe2. Supplier 1 (S1) offers to supply 60MWh at 10€/MWh in Pe1, Supplier 2 (S2) offers 60MWh at 40€/MWh in Pe2 and Supplier 3 (S3) offers to supply 100 MWh in Pe1 and Pe2 as a block at an average price of 30€/MWh.

Table 5-2: Example of Auction with Block Order

Period 1 (Pe1)		Period 2 (Pe2)	
Demand	Supply	Supply	Demand
$(Q_5@P_5)$: 100MWh @90€/MWh	S1 $(Q_1@P_1)$: 60MWh @10€/MWh	S2 $(Q_2@P_2)$: 60MWh @40€/MWh	$(Q_6@P_6)$: 150MWh @90€/MWh
	S3 $(Q_{3/4}@P_{3/4})$: 100MWh@30€/MWh		

Figure 5-2 illustrates both possibilities, being accepting or rejecting the block. Without the block, the price in Pe1 and Pe2 is 90€/MWh. The prices are found at intersection of the order curves derived from the hourly orders (Figure 5-2).

Accepting the block means that a supply order of price zero is added to both periods so that the supply curve shifts to the right and prices drop to respectively 0-10 and 40€/MWh in Pe1 and Pe2. Most exchanges take the middle price of a vertical segment, meaning that the price in Pe1 would be 5€/MWh so that the average price is 22,5€/MWh ((5+40)/2). This is not a feasible solution as the average price is lower than the price limit of the supply block. Therefore the only feasible solution is to reject the block. Note that the middle price assumption has no impact in this example, as the average market price cannot be higher than 25€/MWh.

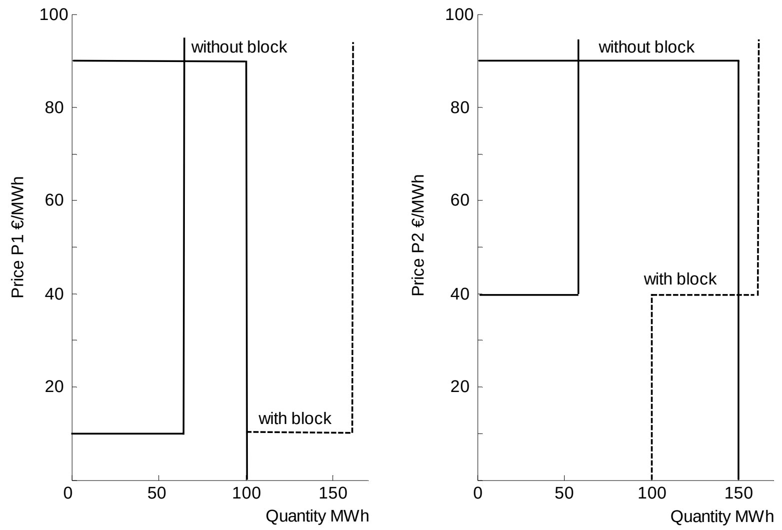

Figure 5-2: Prices with and without block offer Example in Table 5-2

In the above example the only feasible solution is to reject the block. As a result the average price is 90€/MWh. At this average market price, the block is in the money because the market price is higher than the price limit of the block. The block could make a profit by supplying at the determined prices and is therefore paradoxically rejected. Still, the block cannot be accepted as long as uniform or linear prices are imposed.

As discussed in chapter 2, exchanges could avoid PRBs by applying nonlinear pricing as in power pools. Under nonlinear pricing side payments can be made to block orders. In the above example, accepting the block results in an average price of 22,5€/MWh, while the price limit of the block is 30€/MWh. If settled at the market prices, the block would therefore incur a loss of 7,5€/MWh. To compensate for this loss, a total side payment of 1500€ (7,5€/MWh*200MWh) is needed. Depending on the approach used, this side payment is then recovered with a uniform charge for the demand side (uplift), or orders are charged proportional to their incurred profit, etc.

5.3 Formal problem

In this section, respectively the auction problem with hourly orders and with hourly orders and block orders is formalized as a constrained optimization problem.

5.3.1 Auction problem with hourly orders

Hourly orders are characterized by the hour (h) in which they are introduced, whether they are supply (i) or demand (j) and by a price (€/MWh) and quantity (MWh) limit (P_h , Q_h) The (hourly) auction problem with only hourly orders, can be formulated as a constrained optimization problem maximizing gains from trade, with accepted order quantities as the decision variables (q_{ih} , q_{jh}):

$$\underset{q}{Max}\left(\sum_j q_{jh}P_{jh} - \sum_i q_{ih}P_{ih}\right) \tag{4.1}$$

Subject to the market clearing constraint, equalizing demand and supply:

$$\sum_i q_{ih} = \sum_j q_{jh} \tag{4.2}$$

and the order constraints:

$$q_{ih} \leq Q_{ih} \tag{4.3}$$

$$q_{jh} \leq Q_{jh} \tag{4.4}$$

5.3.2 Auction problem with hourly orders and blocks

The following two sections introduce the basic problem (MILP1), which requires nonlinear pricing and the problem as solved by exchanges, which allows linear pricing (MILP2). Both models are Mixed Integer Linear Problems (MILP).

5.3.2.1 MILP1

Block orders are characterized by the hours included in the block (H), whether they are supply (k) or demand (l) and by an average price (€/MWh) and quantity (MWh/h) limit (P , Q).

Adding blocks to the auction problem means that the hourly auction problems have to be solved jointly. Furthermore, binary variables ($b1 = 1$ if block is accepted; $b1 = 0$ otherwise) are used to implement the fill-or-kill constraint of block orders, making them indivisible, i.e. they have to be accepted fully or not at all. To simplify the notation, an hourly quantity ($Q_h = 0$ if $h \notin H$) limit is used for all blocks even if they only apply to a few of 24 hours.

Given the above, every day exchanges have to solve the following auction problem with blocks, with accepted order quantities as the decision variables (q_{ih}, q_{jh}, q_{kh}, q_{lh}):

$$Max \sum_h \left(\sum_j q_{jh} P_{jh} + \sum_l q_{lh} P_{lh} - \sum_i q_{ih} P_{ih} - \sum_k q_{kh} P_{kh} \right) \tag{4.5}$$

Subject to market clearing constraints, equalizing demand and supply in every hour of the day is given by:

$$\forall h: \sum_i q_{ih} + \sum_k q_{kh} = \sum_j q_{jh} + \sum_l q_{lh} \tag{4.6}$$

and the order constraints:

$$q_{ih} \leq Q_{ih} \tag{4.7}$$

$$q_{jh} \leq Q_{jh} \tag{4.8}$$

$$q_{kh} = b1_k Q_{kh} \tag{4.9}$$

$$q_{lh} = b1_l Q_{lh} \tag{4.10}$$

Note that (4.9) and (4.10) are different from (4.7) and (4.8). The accepted quantity of an hourly order can have any positive value smaller or equal to the quantity limit, while a block has a fill-or-kill constraint. The binary variable can only be zero or one so that because of (4.9) and (4.10), the accepted quantity can only be equal to the quantity limit of the block or to zero. Furthermore a single binary variable is used so that putting the variable to 1, means equalizing the decision variable to the order quantity in all hours included in the block. Note that because $Q_h = 0$ for the hours not included in the blocks, the decision variable will automatically be zero for the hours not included in the block.

Solving (4.5) to (4.10) for the example illustrated in section 5.2, implies accepting both demand orders completely, S2 for 50 MWh (5/6), and to accept the 100 MWh block order, yielding total gains from trade of 14500€ (100x90+150x90-100x2x30-50x40). The shadow prices of the market clearing constraints (4.6) are 0-10€/MWh (Pe1) and 40€/MWh (Pe2). As explained in the previous chapter, if the market is cleared on a vertical, different solver software can yield a different price. However, the average price is between 22.5 and 25€/MWh, which is not enough to pay the block.

As explained previously, nonlinear prices are necessary to clear this solution. In other words, the example shows that the solution to the problem (4.5) to (4.10) does not necessarily allow linear prices.

5.3.2.2 MILP2

As illustrated in section 5.2, exchanges look for a market outcome that allows linear prices. This market outcome is further characterized as follows:

- First, block orders can be paradoxically rejected, but accepted blocks are always in the money (otherwise the solution is not feasible).
- Second, the hourly order incentive conditions are satisfied.

Constraints with the hourly prices (p_h) as decision variables need to be added to the problem (4.5)-(4.10) to guarantee the above. First, constraints are necessary to guarantee that accepted blocks are in the money, with nH the number of hours included in a block and $P_{\max}$ the maximum admissible price for an order[35].

$$\forall k : b1_k \, nH_k P_k \leq \sum_{k \in H_k} p_k \tag{4.11}$$

(4.11) reads as follows: the price limit (P_k) of a block offer is a lower bound for the average market price ($\sum_{k \in H_k} p_k / nH_k$) of the hours included in the block, if the offer is accepted ($b1_k = 1$), while there is no such bound if the order is rejected ($b1_k = 0$). In other words, if the supply block is accepted, the average market price should be at least as high as the price limit of the blocks.

$$\forall l : \sum_{l \in H_l} p_h \leq nH_l (P_l + P_{\max} (1 - b1_l)) \tag{4.12}$$

(4.12) reads as follows: the price limit (P_l) of a block bid is an upper bound for the average price ($\sum_{k \in H_k} p_l / nH_l$) of the hours included in the block, if the order is accepted ($b1_l = 1$), while there is no such bound if the order is rejected ($b1_l = 0$). In other words, if the demand block is accepted, the average market price should not be higher than the price limit of the block.

Second, constraints are necessary to satisfy the incentive conditions of hourly orders, with $b1_h$ a binary variable equal to one if the hourly order is accepted (and zero otherwise) and $b2_h$ a binary variable equal to one if the hourly order is partially accepted (and zero otherwise).

---

[35] Note that all exchanges have a maximum price (Pmax) for practical reasons. This price should not be seen as a price cap but rather as a sufficiently large number to protect from faulty input.

$$\forall i,h : b1_{ih} P_{ih} \le p_h \qquad (4.13)$$

(4.13) reads: the price limit of a hourly offer (P_{ih}) is a lower bound for the hour price (p_h), if the offer is (partially or completely) accepted ($b1_{ih} = 1$), while there is no such bound if the order is rejected ($b1_{ih} = 0$).

$$\forall j,h : p_h \le P_{jh} + P_{\max}(1 - b1_{jh}) \qquad (4.14)$$

(4.14) reads: the price limit of a hourly bid (P_{jh}) is an upper bound for the hour price, if the order is (partially or completely) accepted ($b1_{jh} = 1$), while there is no such bound if the order is rejected ($b1_{jh} = 0$).

$$\forall i,h : p_h \le P_{ih} + P_{\max}(b1_{ih} - b2_{ih}) \qquad (4.15)$$

(4.15) reads: the price limit of the hourly offer (P_{ih}) is an upper bound for the hour price (p_h), if the order is rejected ($b1_{ih} = b2_{ih} = 0$) or partially rejected ($b1_{ih} = b2_{ih} = 1$), while there is no such constraint if the order is completely accepted ($b1_{ih} = 1, b2_{ih} = 0$).

$$\forall j,h : P_{jh} - P_{\max}(b1_{jh} - b2_{jh}) \le p_h \qquad (4.16)$$

(4.16) reads: the price limit of the hourly bid (P_{jh}) is a lower bound for the hour price (p_h), if the order is rejected ($b1_{jh} = b2_{jh} = 0$) or partially rejected ($b1_{jh} = b2_{jh} = 1$), while there is no such constraint if the order is completely accepted ($b1_{jh} = 1, b2_{jh} = 0$).

In other words, (4.13) to (4.16) implies that hourly orders are accepted when they are in the money and hourly orders out of the money are rejected. Furthermore, satisfying these constraints implies that partially accepted orders set the price, i.e. the hourly price equals the price limit of the order.

Solving (4.5) to (4.16) for the example illustrated in section 5.2, implies curtailing demand in both periods to 60 MWh, and to accept S1 and S2 completely, yielding a total gain from trade of 6600€ (60x90+60x90-60x10-60x40). The resulting prices are 90€/MWh in both periods, which are the price limits of the curtailed demand bids. In other words, the constraints are binding and have resulted in one PRB and a loss in gains from trade of 7900€ (14500-6600). This is the price to pay for imposing linear prices.

5.4 Representative scenarios

APX is the only power exchange that makes its aggregated order curves of every hour publicly available. Other exchanges sometimes make these curves available to their participants, but not publicly. 19 historical days have been randomly selected (Table 5-3). These days are from different years, seasons, week-weekend. The hourly orders are extracted from these curves. Every scenario includes the hourly orders of one of these days. Pmax is assumed to equal 2500€/MWh, as at APX.

Table 5-3: Days used to distract hourly orders for scenarios

Date (DD/MM/YY)	Average price (€/MWh)	Maximum price (€/MWh)	Total traded volume (MWh)
15/01/03	32	108	32636
27/03/03	30	41	31240
20/05/03	33	91	32874
04/07/03	33	100	27691
22/11/03	36	96	34102
22/02/04	20	26	34474
19/04/04	29	41	35864
15/06/04	35	70	31357
18/08/04	31	44	35279
21/10/04	32	42	38886
10/12/04	36	75	46350
29/01/05	33	44	50146
10/02/05	36	45	42239
25/03/05	39	60	46373
03/04/05	26	50	40843
07/05/05	32	42	42964
25/05/05	43	80	35119
26/06/05	31	46	47448
20/07/05	45	63	47792

As mentioned in section 5.1, blocks represent up to 20% of the volume traded on the exchanges. Accepted block volume is included in the aggregated order curves, as price taking orders, but cannot be distinguished from real price taking orders. Instead of trying to extract block information from these curves, blocks have been randomly generated. To every scenario a randomly generated set of blocks is added. Block sets have been generated as follows:

- 100 has been assumed to be a realistic *amount of blocks*. The number of blocks in a scenario has been determined as a random integer, smaller than 200.
- Equal distribution between *demand* and *supply* blocks has been assumed realistic. When generated, every block has 50% probability of being a

purchase block order or a supply block order. In other words, not all scenarios have such an equal distribution but the average scenario does.

- It has been assumed that blocks are price-setting orders, meaning that their prices are significantly different from zero and close to the market prices. The *price limit* is a random deviation, smaller than 10%, from the average price of the day, which would have been the average day price if no blocks were added to the scenario.
- Block *size* restrictions are publicly available information. As discussed in section 5.1, EEX allows up to 250MWh/h sized blocks, while other exchanges only allow smaller blocks. For every scenario, a maximum block size (MWh/h) is generated as a random integer between 10 and 300. Consequently the size of the blocks in that scenario is random, but smaller than the maximum block size.
- Block *type* restrictions are publicly available information. Table 5-1 in section 5.1 illustrates the 11 types of blocks that can be traded at EEX. For instance, at Powernext the 10 types[36] illustrated in Table 5-4 can be traded. On APX, participants can freely choose which hours to include in the block. Every combination of consecutive hours can be made, which means that 354 (=24+23+22+…+1) block types can be traded. Every scenario has a 50% probability of having a block type restriction. If there are no restrictions, all combinations of consecutive hours are possible as at APX. If there is a restriction, every block is randomly one of the 10 types traded on Powernext.

Table 5-4: Block products at Powernext

Contract name	Time interval under block contract
Block Bid 1-4	00.00h – 04.00h (covering hours 1 to 4)
Block Bid 5-8	04.00h – 08.00h (covering hours 5 to 8)
Block Bid 9-12	08.00h – 12.00h (covering hours 9 to 12)
Block Bid 13-16	12.00h – 16.00h (covering hours 13 to 16)
Block Bid 17-20	16.00h -20.00h (covering hours 17 to 20)
Block Bid 21-24	20.00h – 24.00h (covering hours 21 to 24)
Block Bid 1-24	00.00h – 24.00h (covering hours 1 to 24)
Block Bid 9-20	08.00h – 20.00h (covering hours 9 to 20)
Block Bid 1-6	00.00h – 06.00h (covering hours 1 to 6)
Block Bid 1-8	00.00h – 08.00h (covering hours 1 to 8)

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[36] June 2006, the website indicates that there are 11 types traded, but when the analysis was performed this was 10.

A batch of 200 scenarios has been created in the manner explained above. The results are presented in the next section, but also chapter 6 and 7 are based on the same batch of 200 scenarios. Batches of 100 scenarios yielded somewhat different results. Increasing the batch size to 200 has proved to be sufficient to present results that are not batch specific. Moreover, scenarios within the batch are diverse enough to indicate sensitivities.

5.5 Paradoxically Rejected Blocks (PRB)

PRBs are a consequence of imposing linear prices. This section clarifies the concept of PRBs. First, two types of PRBs are distinguished. Second, an urban legend concerning PRBs is countered.

5.5.1 Depth of PRB

As discussed in section 5.3.2.2, in the two-period example with one supply block the only feasible solution is to reject the blocks yielding an average market price of 90€/MWh. In this example the PRB is deep in the money, i.e. there is large difference between the average market price and the price limit of the block (ΔP).

In the batch of scenarios discussed previously, MILP2 yields 4,15 PRBs per day on average, with a maximum of 27 in a day. In total for the 200 scenarios there are 829 PRBs, while there are 19619 blocks in total in these scenarios. Therefore, the likelihood of block to be paradoxically rejected is only 4%, which is further discussed in the chapter 7.

As illustrated in Figure 5-3 almost 40% of these PRBs are actually not loosing any money, i.e. the price limit is equal to the average market price (ΔP=0). Still, these traders want to be accepted so that they should be counted. However, applying nonlinear pricing is not a solution for PRBs with a zero ΔP. These blocks will not receive any compensation, as they are not in the money. Therefore, they are not taken into account in chapter 8.

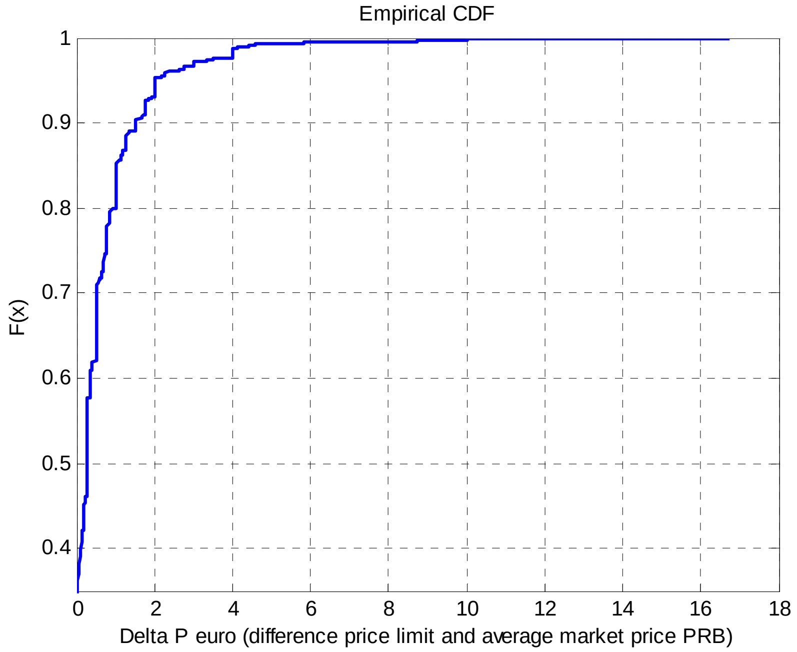

Figure 5-3: ΔP of PRBs in MILP solution

5.5.2 Common wisdom PRB

Amongst traders and exchanges it is often said that if blocks cannot be accepted completely, they can become rejected fully, suggesting that the indivisibility is causing paradoxical rejection. To check the truth of this commonly accepted explanation for the phenomenon of PRBs, all scenarios have been rerun leaving out the fill-or-kill constraint of blocks. (4.9) and (4.10) impose the indivisibility of blocks. These constraints have been replaced by the following to make blocks divisible:

$$q_{kh} \leq b1_k Q_{kh} \tag{4.17}$$

$$q_{lh} \leq b1_l Q_{lh} \tag{4.18}$$

With divisible blocks, the total number of PRBs in the 200 scenarios reduces from 829 to 112, with a mean of 0,56 and a maximum of 5.8 PRBs per day. In other words, the inter-temporal rigidity of blocks alone is sufficient to cause paradoxical rejection.

5.6 Conclusions

Blocks are important for traders and exchanges. An auction with blocks is a special type of combinatorial auction. This chapter has provided a model to study the auction problem with blocks. Furthermore, a batch of representative scenarios has been introduced. The model and scenarios are used in the next three chapters to further study the auction problem with blocks.

4% of the blocks are PRB when applying the linear pricing approach of exchanges to the batch of scenarios. However an important distinction has been made between PRBs that are actually losing money due to a lost trade opportunity and blocks that were rejected with a price limit equal to the average market price. When studying the difference between linear and nonlinear pricing in chapter 8, the second type of PRB should not be counted. As argued, nonlinear pricing is not a solution for this type of PRB, as these rejected blocks would not receive compensation.

Finally, despite what is often said among traders and exchanges, the phenomenon of paradoxically rejection is not only caused by the fill-or-kill constraint of a block. The inter-temporal rigidity in itself is sufficient to cause PRBs.

Chapter 6

Computational complexity auction problem with blocks

6.1 Introduction

The previous chapter has formalized how exchanges deal with blocks. The constrained optimization model with binary variables for blocks and constrained continuous variables for hourly orders are Mixed Integer Problems (MIP), which are difficult to solve. The available commercial software has evolved substantially the last decade, but there is still the fundamental problem that in the worst case all combinations have to be enumerated to select the optimal solution, i.e. the problem is computational intractable.

First, the computational complexity of the auction problem with blocks as faced by exchanges is further discussed. Some exchanges actually have a more difficult problem to solve than the problem formalized in the previous chapter. Second, a simple but fast algorithm is introduced that yields a feasible but not necessarily optimal solution. Third, the solution of this simple algorithm is compared with the optimal solution (MILP2 of the previous chapter) to quantify the exposure to sub-optimal heuristic solutions.

6.2 Computational complexity

The auction problem with blocks (4.5) to (4.16) assumes a flat hourly order system. In Europe, there are actually two hourly order formats, sometimes referred to as flat orders and orders with interpolation. In both systems participants submit supply and demand curves by submitting price-quantity (P,Q) pairs. However, under a flat order system this implies introducing a step curve as illustrated in Figure 6-1, while under an order system with interpolation this implies introducing a piecewise linear curve as illustrated in Figure 6-2.

Omel, APX and Borzen for instance use the flat order system. Nord Pool and Powernext for instance use the order system with interpolation. Note that the MILP1 and 2 assume that there are no slopes in the curves so that they can be cut up in orders of a certain quantity with a flat price limit. Due to the slopes in the curves of an order system with interpolation, the objective function would be quadratic so that the problem is a Mixed Integer Quadratic Problem (MIQP).

MIQP solvers exist but are not well developed. Therefore a flat order system is assumed to run simulations.

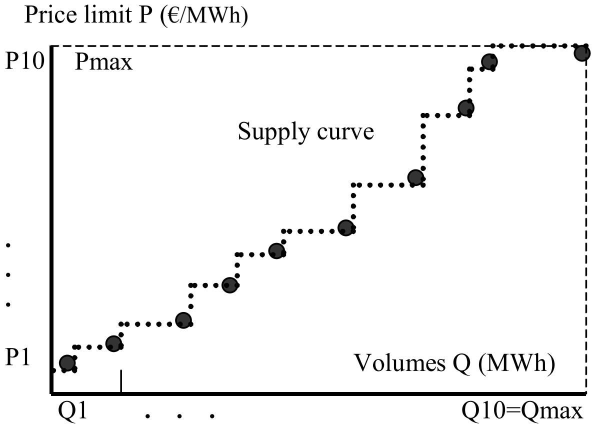

Figure 6-1: Supply curve without slopes: flat hourly order system

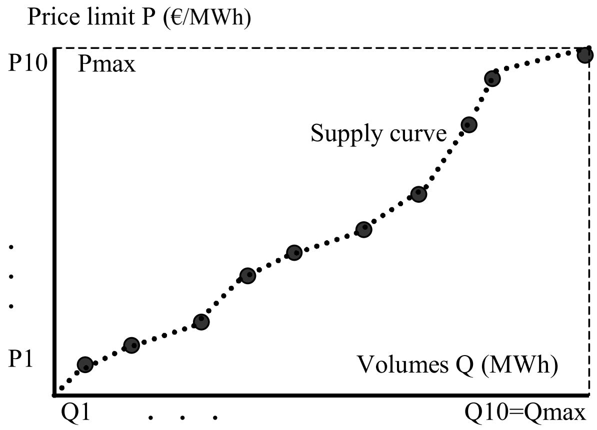

Figure 6-2: Supply curve with slopes: hourly order system with interpolation

It is important to note that on the one hand exchanges with interpolation have a more difficult problem to solve, but on the other hand they do are not exposed to horizontals so that they do not have indeterminacies in quantities (see chapter 4). However, they are confronted with indeterminacies in prices because the horizontal aggregation of two curves above each other yields a vertical that connects the two order curves.

6.3 Lower Bound performance Algorithm (LBA)

As explained in section 5.2, the heuristic approach of exchanges consists of a block selector and a coordination module that determines the prices for a fixed block set. Figure 6-3 illustrates the process model of a very simple algorithm based on such a decomposition of the auction problem with blocks. The algorithm initializes by selecting all blocks. If that solution is not feasible, the algorithm continues by selecting a block to go out. The process is repeated until a feasible combination of blocks is found. The first feasible solution that is found is the final solution provided by the algorithm.

The selection of blocks to go out is based on criteria also applied by exchanges, as indicated on their websites. The block with an average price limit that deviates most from the average market price, is selected to go out first. If there is a tie, the smallest block is selected first. If there is still a tie after that (in the case of identical block orders), the block submitted last is selected to go out first.

The reasoning behind these criteria is that the block that is most out of the money (average price that deviates the most from the average market prices) is less likely to be part of the optimal combination. Putting out other blocks does not easily result in the block being in the money. It is more interesting to keep blocks that are almost in the money in the selection, as a relative small change in prices, triggered by changing the block set, could put them in the money. On the other hand, rejecting large blocks is giving up on a lot of potential surplus. Therefore, from a gains from trade point of view it can be more interesting to keep a large block in the selection, even though it is more out of money than a smaller block. Some exchanges therefore select blocks to go out based on the price difference multiplied with the size of a block. However, this is not necessarily better as finding the optimal combination of blocks is much more complex than this simple reasoning.

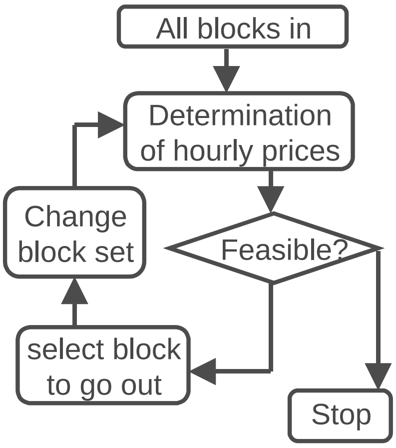

Figure 6-3: Process model of the Lower Bound performance Algorithm (LBA) for the heuristic approach of exchanges

To guarantee finding the optimal solution, the block selector has to be such that all combinations of blocks are tried for feasibility so that the best in terms of gain from trade can be selected. For N blocks there are 2^N block combinations. The above-described algorithm (LBA) guarantees to find a feasible solution after trying N block combinations. It can therefore not guarantee finding the optimal solution, but it is much faster, especially for problems with many blocks.

The feasible solution that is guaranteed to be found by LBA after trying N block combinations, is the solution without blocks, which is how the procedure ends. The performance guarantee is therefore very poor, i.e. scenarios exist in which the algorithm performance is not better than an algorithm that simply rejects all blocks from the start. However, this does not mean that the algorithm will perform badly in representative scenarios. The quality of the LBA solution in representative scenarios is a good indication for the exposure to suboptimal solutions of the specialized heuristics used in practice.

6.4 Exposure to sub-optimal heuristic solutions

The batch of scenarios introduced in the previous chapter is used to indicate the exposure of exchanges to sub-optimal solutions when applying heuristic procedures to clear their market. First, the calculation time of the software used to calculate the optimal solution is discussed. Second, the exposure respectively in terms of gains from trade and PRBs is discussed.

6.4.1 Calculation time MILP

The scenarios have been solved for MILP2 on a Pentium® IV, using the CPLEX® solver software called from Matlab® using the Tomlab® interface.

In two scenarios, the optimal solution was not yet found after 2.5 days so that the solver was stopped. For all other scenarios in the batch of 200 scenarios, the solver calculation time was 4 minutes on average. The minimum and maximum calculation time was respectively a few seconds and 3.5 hours. 50% of the scenarios solved in less than one minute and 95% less than 10 minutes. This is typical for the performance of commercial MILP solvers. No MILP solver can guarantee to find the optimal solution fast, but the best available solvers find the optimal solution fast in most cases. As said in O'Neill et al. (2005), today's MILP solvers are quasi as fast as LP solvers 10 years ago for equally sized problems.

In other words, heuristics are necessary because exchanges have to clear their markets in a time frame of minutes and commercial solvers cannot always find the optimal solution to MILP2 in that time frame. Of course, exchanges could run the MILP2 in parallel to their heuristics to use the latter as a backup solution. Note that this is only true for the exchanges with a flat order system. As discussed in section 6.1, several exchanges actually have to solve a MIQP.

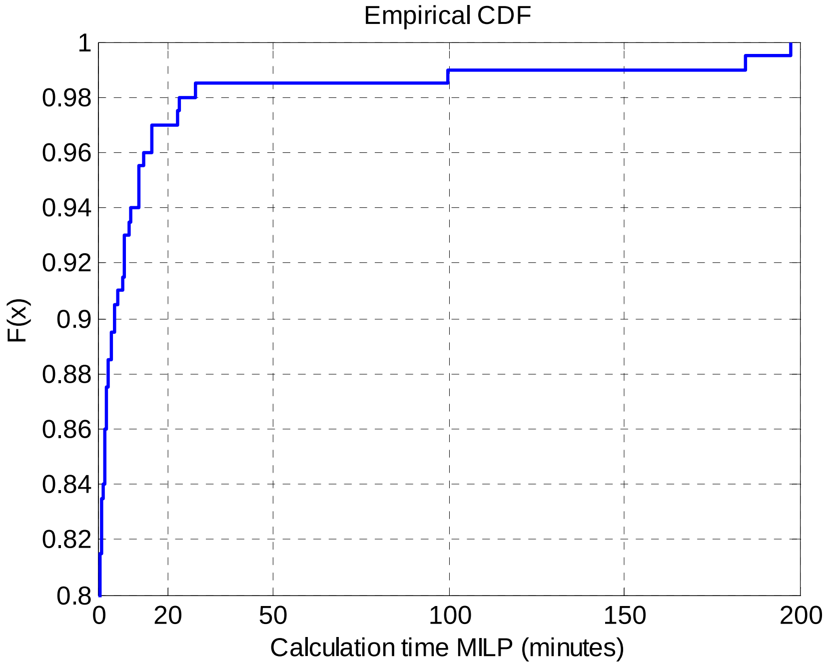

Figure 6-4: Calculation time MILP2 (minutes) of all scenarios except two that were stopped after 2.5 days

Pekec and Rothkopf (2005) discuss non-computational approaches to mitigating computational problems in combinatorial auctions. Limiting the combinations participants are allowed to bid is described as an effective way to reduce the computational complexity of combinatorial auctions. Park and Rothkopf (2005) even propose an auction with bidder-determined allowable combinations.

Also in combinatorial electric energy auctions this is true. As mentioned in the previous section, in 50% of the scenarios blocks can consist of every combination of consecutive hours, while in the other 50% of scenarios all blocks are one of the 10 combinations that are allowed at Powernext. In the terminology of this text, most exchanges such as Powernext have a block type restriction. For most scenarios, there is no significant difference. However, all scenarios that needed to be stopped after running more than a day, such as the two scenarios in this batch that were stopped after 2.5 days have been scenarios without a type restriction. As illustrated in Figure 6-5, also for the scenarios that were solved, the most extreme outliers were all scenarios without a type restriction.

One could also expect a correlation between the number of blocks and the solver time, as the number of block orders increases the problem size in terms of binary decision variables, but such a correlation could not be found (=0.041). Furthermore, coherence with other block characteristics could not be found. However, there is a substantial difference between the calculation time of MILP1 and MILP2. In this batch of scenarios, MILP1 only took 0,6 seconds on average to solve with a maximum of 1,4 seconds. In other words, these results clearly indicate that the real computational complexity of MILP2 comes from the constraints that are necessary to allow linear pricing.

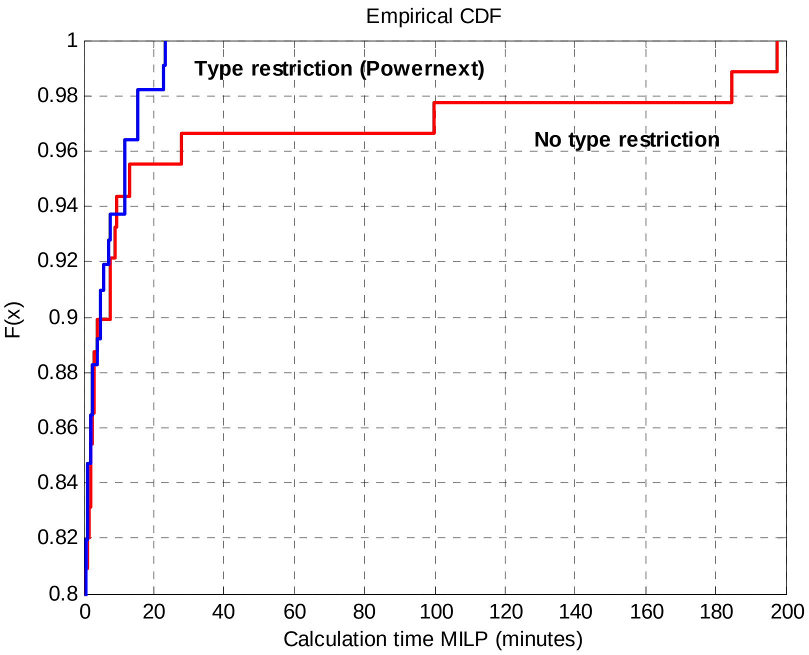

Figure 6-5: Calculation time MILP2 (minutes) with and without type restriction

6.4.2 Heuristic exposure in terms of gains from trade

As illustrated in Figure 6-6, this difference is relatively small. Most of what can be gained by adding blocks is already achieved by LBA. On average the difference is 0,04% and never higher than 1%. The reason is that even in a solution without blocks, gains from trade are very high due to the hourly orders.

In absolute terms, the difference between the MILP2 and LBA is 2488€/day on average going up to 77,902€/day. A simple t-test for the null hypothesis that both averages are equal assuming a normal distribution and equal standard deviations yields a p-value[37] of 0,9889. This implies that the null hypothesis cannot be rejected so that the difference in gains from trade is not statistically significant.

However, when projected on a longer time horizon, a substantial amount of euros can be gained by designing a heuristic search algorithm that finds a set of blocks closer to the optimal set than LBA. For instance, the cumulated difference over the batch of 200 scenarios is almost half a million €.

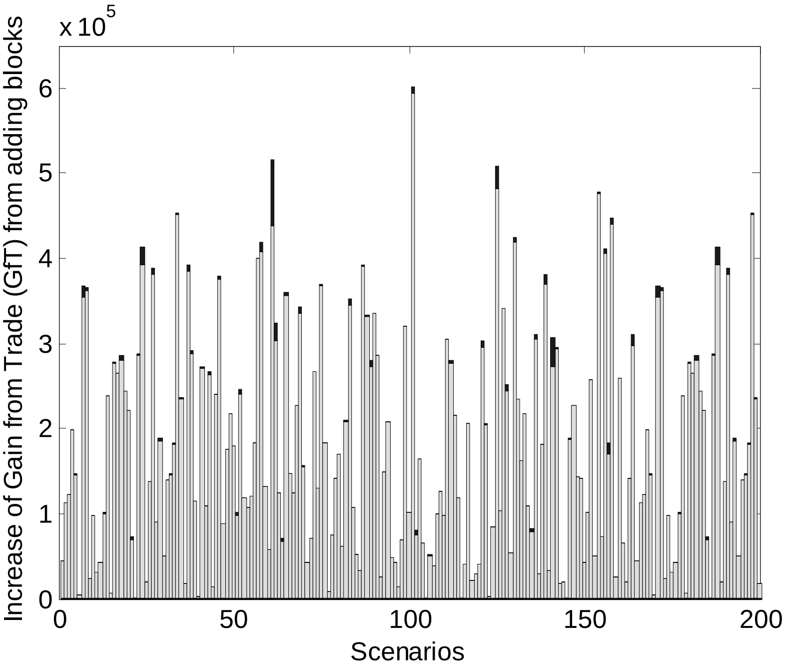

Figure 6-6: Heuristic exposure in terms of gains from trade (light bar: LBA, dark bar: MILP-LBA)

6.4.3 Heuristic exposure in terms of PRB

LBA almost yields 8,13 PRB on average and a maximum of 49, which is almost the double of MILP2. A simple t-test for the null hypothesis that both averages are equal

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[37] The p-value is the probability of observing the given result by chance given that the null hypothesis is true. In other words, the higher the p-value is, the more likely the null hypothesis.

assuming a normal distribution and equal standard deviations yields a p-value of 0,0000024. This implies that the null hypothesis can be rejected so that the difference in terms of PRBs is statistically significant.

Figure 6-7 illustrates the exposure to PRBs due to using heuristics. The Cumulative Distribution Function illustrates that in up to 50% of the scenarios both solutions yield an equal amount of PRBs. Furthermore, in a bit more than 5% of the scenarios, LBA even yields less PRBs. This indicates that maximizing gains from trade does not always minimize the number of PRBs.

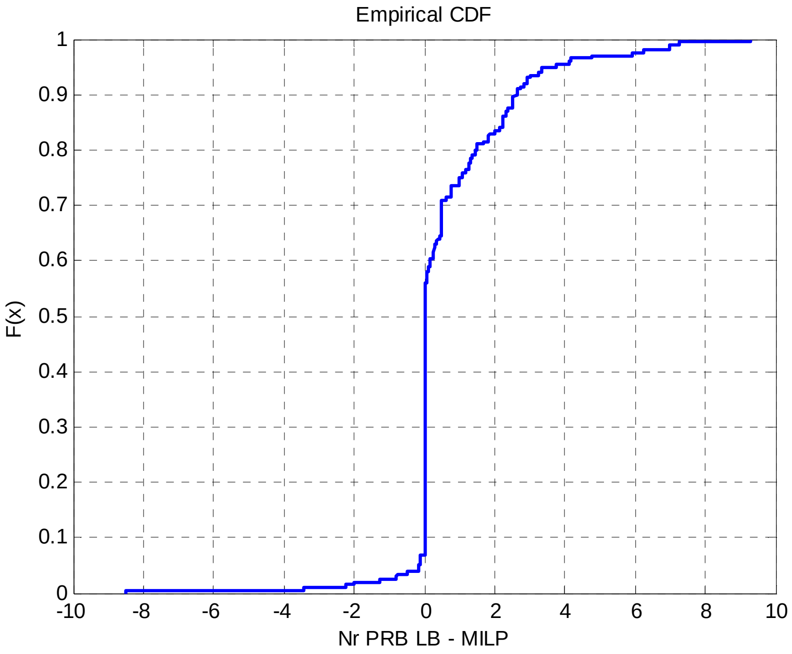

Figure 6-7: Heuristic exposure in terms of PRB

6.5 Conclusions

The computational complexity of the auction problem with blocks is such that heuristics need to be used. The detailed procedures used in practice are not publicly available. The optimal solution to the constrained optimization model (MILP2) introduced in the previous chapter is the upper bound for the performance of the heuristics used in practice.

Furthermore, all exchanges decompose the problem in a block selector and a coordination module that determines the prices for a fixed block set. A simple algorithm (LBA) based on such decomposition has been introduced that can be used as a lower bound performance measure for the heuristics used in practice.

The scenarios introduced in the previous chapter have been used to indicate the exposure to sub-optimal solutions. The scenarios indicate a substantial gap between the MILP2 solution and the LBA solution; both in terms of gains form trade and number of PRBs. In other words, a well-designed heuristic search algorithm is important. In the next two chapters, the auction problem with blocks is further analyzed, without considering computational complexity.

Chapter 7

Block order restrictions

7.1 Introduction

The previous two chapters introduced the auction problem with blocks, how it can be modeled and its computational complexity. This chapter analyses the rationale of block order restrictions. All exchanges restrict the size (MWh/h) or the type (span in terms of hours) or the number of blocks that can be introduced per participant per day. There is no methodology available to impose such restrictions. This can partly explain why all exchanges have very different restrictions.

The attractiveness of a block in comparison with hourly orders comes from its indivisible and multi-period character. However, blocks can become paradoxically rejected, which makes them less attractive. The question could therefore be raised whether restricting the use of blocks reduces the problem of PRBs. The results indicate that this is not an effective way to reduce the problem of PRBs so that there is no reason to impose such restrictions, as it will only reduce the volumes traded on exchanges and will oblige traders to find alternatives.

First, the constraints block order restrictions impose on traders are discussed. Second, the number and likelihood of PRBs in representative scenarios is indicated in function of these restrictions. Finally, the rationale behind restrictions is questioned and recommendations are provided.

7.2 Constraint for traders

Most exchanges have restrictions on block orders. As illustrated in Table 7-1, there are substantial differences between exchanges. Powernext does not restrict the number of block orders that can be submitted per participant per day, while the size is for instance more restricted on APX (50MWh/h) than on EEX (250MWh/h). On APX, participants are allowed to make any combination of consecutive hours. Powernext and EEX on the other hand restrict blocks to 10 or 11 types (the types are discussed in chapter 5).

The number of blocks that can be introduced to an auction per day is never really restricted as the amount of participants is not restricted. Market parties could even register more than once to avoid this restriction, although this increases transaction costs. In other words, this restriction is actually only a discouragement to market parties.

A size restriction is binding for traders, as generation units are easily larger than 50MW, but also larger than 250MW. A 250MW generator faced with a restriction of 50MWh/h could submit 5 blocks of 50MWh/h. However, this would mean he is exposed to the risk that some of the blocks could become paradoxically rejected. If he is only able to produce 250 or nothing this means he is exposed to balancing penalties.

A type restriction is binding for traders, as it can be that a trader wants to sell or purchase a contract for a combination of hours that is not allowed. Note however that most trade is in standardized periods such as base and peak load. Block types traded on exchanges encompass these typical combinations of hours that are most important for trade.

What these restrictions mean for trade efficiency is very uncertain. Faced with these restrictions, traders could choose to act in the consecutive bilateral markets operating before and after the day-ahead auction. They could also introduce price taking hourly orders at the day-ahead auction and hedge the price risk with futures or other financial derivatives. Therefore, it depends on the availability and transaction costs of the alternatives.

What is certain is that by imposing such restrictions, exchanges will attract less volume. In the extreme case, traders would stop using blocks, as their use is too restricted.

Table 7-1: Block order restrictions on APX, Powernext and EEX

	Nr block types	Max nr blocks / day / participant	Max size (MWh/h)
APX	354[1]	50	50
Powernext	10	INF[2]	100[3]
EEX	11	6	250

1 All combinations of consecutive periods are allowed
2 Per portfolio it is possible to submit every type once, but participants can submit several portfolios
3 Before 2005 it was 50MWh/h

7.3 Rationale of restrictions

As argued in the previous section, restricting the number of blocks that can be introduced by a participant per day does not restrict the total number of blocks that can be introduced. However, it will discourage market parties to submit many blocks, as it is expensive to have more than one subscription to the exchange. Furthermore, type and size restrictions are binding for traders.

The attractiveness of a block in comparison with hourly orders comes from its indivisible and multi-period character. However, blocks can become paradoxically rejected, which makes them less attractive. As discussed in chapter 5, the deeper in the money and the larger the block, the larger the opportunity cost is of being excluded from trade. The opportunity cost linked to a PRB is equal to its size times the number of hours it covers multiplied with its depth[38]. Therefore, this section analyzes whether block order restrictions effectively reduce the visible problem of PRBs.

The numerical results that are presented are based on the MILP2 model and the batch of representative scenarios introduced in chapter 5. First, some PRB statistics for the whole batch of scenarios are given. Second, the effectiveness of restrictions in reducing the problem of PRB is discussed.

7.3.1 PRB statistics

In the batch of scenarios designed to study the auction problem with blocks, the number of PRBs is large. On average there are 4 PRBs per day with a maximum of 27 PRB in one day. The likelihood of PRBs is small on average but is high in some scenarios. When introducing a block, on average there is a 4,36% probability that it will be paradoxically rejected, with a maximum of 50%. However, the probability of small blocks (<50MWh/h) being paradoxically rejected is much smaller, i.e. 1% on average with a maximum of 10%.

In other words, risk of being paradoxically rejected is not such that it is an important issue for traders. Furthermore, the results indicate that traders that submit smaller blocks are less likely to be paradoxically rejected. Table 7-2 summarizes these findings.

Table 7-2: PRB statistics

	Mean	Max
Nr PRB	4.1450	27
Likelihood PRB (Nr PRB/Nr blocks)	0.0436	0.5000
Likelihood PRB blocks < 50MWH/h	0.0101	0.1250

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[38] The difference between the average market price and the price limit of the block.

7.3.2 Effect of restrictions on PRB

The results in the previous section are based on a batch of scenarios with:

- Maximum block sizes going up to 300MWh/h, which is larger than allowed on most exchanges (in Table 7-1 the maximum with 250 MWh/h).
- Total number of blocks going up to 200 per day, whereas a realistic number is 100 per day.
- More or less half of the scenarios with only the 10 Powernext block types, and the other half of the scenarios with blocks of all possible types.

By imposing restrictions, the exchange can for instance make sure that scenarios with many large blocks are avoided. The rational could be that this way exchanges reduce the visible problem of PRB.

Type restriction

As discussed in chapter 5, restricting the allowed combination of hours in a block reduces the calculation time of the MILP2 model. In other words, the computational complexity of the auction problem is reduced. Therefore it could be argued that the exposure to sub-optimal heuristic solutions is reduced, also in terms of number of PRBs. However, the analysis presented in this chapter makes an abstraction of computational complexity.

All scenarios in the batch of representative scenarios can be categorized into scenarios with a type restriction (meaning that all blocks are one of the 10 types traded on Powernext) and scenarios without a type restriction (meaning that all combinations of consecutive hours are possible as on APX). Table 7-3 illustrates some statistics for the two samples. Even though the means and standard deviations are different, this difference is not statistically significant[39]. In other words, there is no significant difference in number of PRB between these categories of scenarios. Therefore, the results indicate that exchanges cannot reduce the visible problem of PRB by imposing a type restriction.

Table 7-3: Effect of block types on PRB

Nr PRB	All types	Powernext types
Mean	3,6292	4,5586
Standard deviation	3,6444	5,2651
Max	15	27

Number of blocks per participant per day

Table 7-4 illustrates that even though there is a significant correlation between the total number of blocks in a scenario and the number of PRBs in that scenario, this is

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[39] The null hypothesis that the means are equal, assuming a normal distribution for both samples and equal standard deviations cannot be rejected for a 5% significance (p-value is 0,1585).

not true for the likelihood of PRBs. In other words, for traders the probability of being paradoxically rejected does not increase if in total more blocks are introduced. The table also illustrates that this is true for blocks in general as well as for small blocks. Therefore, exchanges cannot reduce the problem of PRBs as perceived by traders by imposing a restriction on the number of blocks that can be introduced per participant per day.

Perhaps the restrictions have been imposed from the logic that every PRB is a potential complaint. Indeed, the number of PRBs can effectively be reduced with this restriction. The traders' concern is however that of the likelihood or the risk of being paradoxically rejected.

Max size restriction

Smaller blocks are less likely to be paradoxically rejected, but this in itself is not a reason to impose the use of small blocks on all traders (see previous section). However, this in itself should not be a reason to impose a block size restriction on all traders. It could be argued that such a restriction is necessary if large blocks submitted by one trader increase the likelihood of paradoxical rejection for all traders. Note that this would also create opportunities for abuse.

As illustrated in Table 7-4, the maximum block size only explains 9,3% of the variations in the number of PRB between scenarios (R^2 of the linear regression). For the likelihood of PRB this is even less. In other words, for traders introducing small blocks, the risk of being paradoxically rejected is not significantly affected by the fact that others introduce larger blocks. Therefore, exchanges cannot reduce the problem of PRBs by imposing a size restriction.

Table 7-4: Effect of nr of blocks and maximum block size on PRB

Correlations (R^2)	Nr blocks	Maximum block size
Nr PRB (Figure 7-1)	0,6407 (41,4%)	0,3053 (9,3%)
Likelihood PRB (Figure 7-2)	-0,0362 (0,13%)	0,2139 (4,6%)
Likelihood PRB blocks < 50MWH/h (Figure 7-3)	0,103 (1%)	0,181 (2,2%)

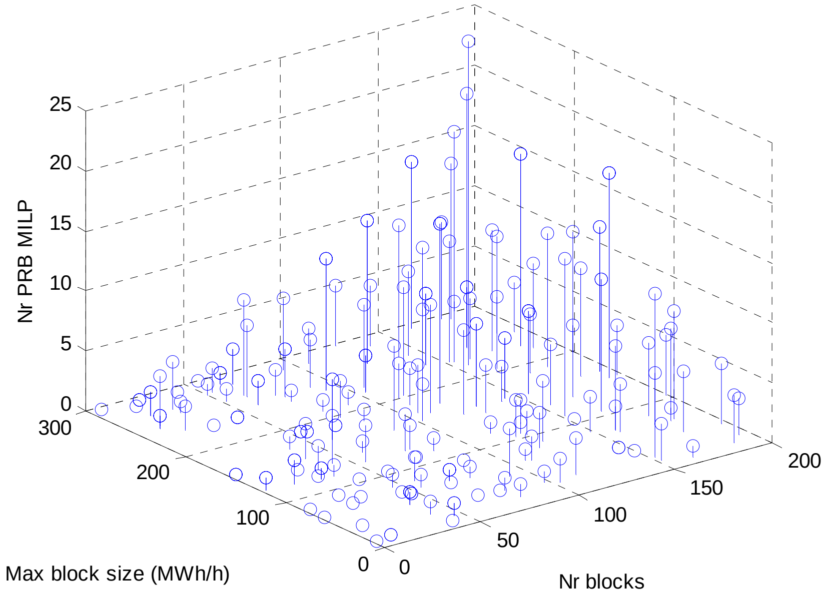

Figure 7-1: Nr of PRB MILP (MILP2 solution)

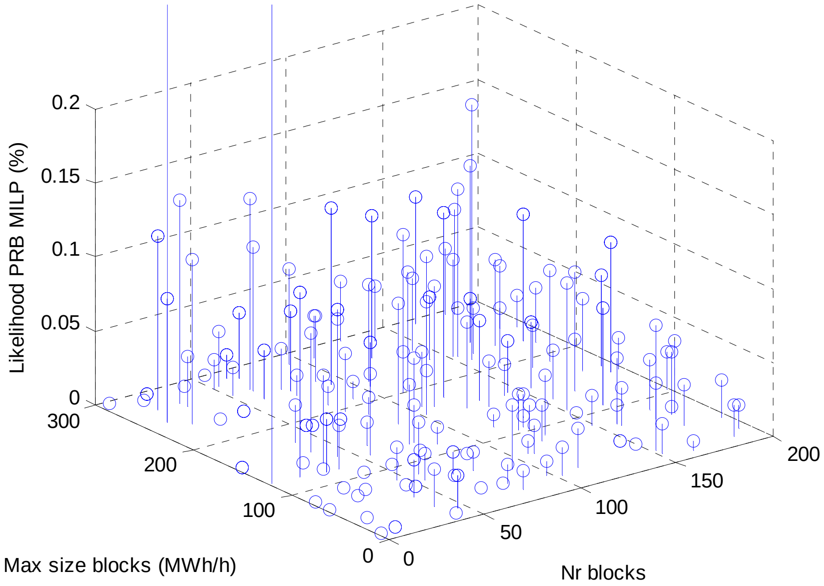

Figure 7-2: Likelihood PRB (MILP2 solution)

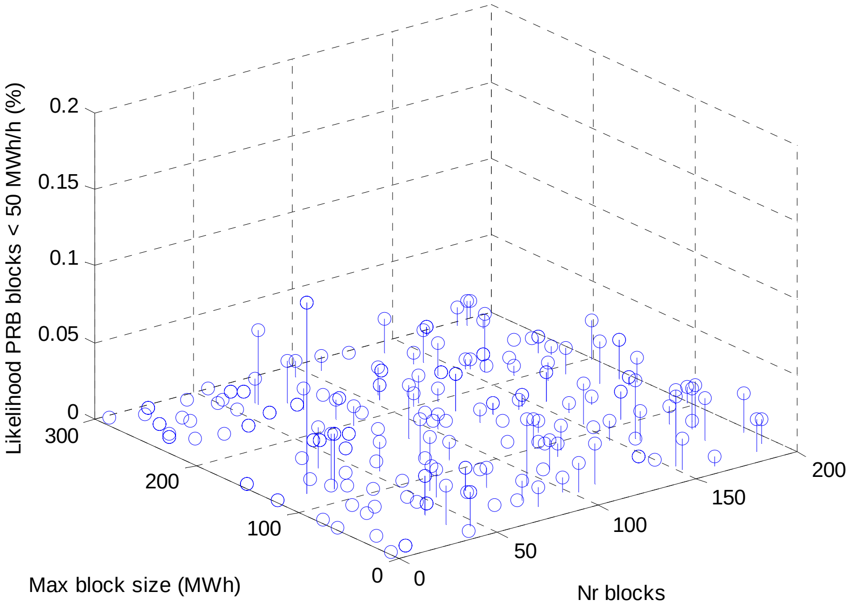

Figure 7-3: Likelihood PRB < 50 MWh/h (MILP2 solution)

7.4 Conclusions

The analysis presented in this chapter clearly indicates that exchanges cannot reduce the problem of PRBs by restricting the type, size or number of blocks that can be introduced per participant per day.

The analysis has shown that the number of PRBs increases with the number of blocks in a scenario. Furthermore, small blocks are less likely to be paradoxically rejected, but this in itself is not a reason to impose the use of small blocks on all traders. A block will not be more likely paradoxically rejected if the total number of blocks introduced to the exchange is larger, nor if also larger blocks or many different types of blocks are introduced. It can therefore be concluded that exchanges restrict too much the use of blocks. It is in their benefit and in the benefit of traders to omit these restrictions.

Block order restrictions are an artificial and ineffective way of reducing the problem of PRBs. If PRBs were a real problem for trade efficiency, they should be avoided with nonlinear pricing, which is discussed in the next chapter.

Note that the analysis in this chapter implicitly assumes that omitting the restrictions on blocks does not reduce the number of hourly orders that are introduced. When an exchange is introduced in an immature market, it does not necessarily have hourly orders for every hour of the day or just a few. This can for instance be observed on the Slovenian exchange Borzen. The situation with many blocks and just a few hourly orders has not explicitly been addressed here. In other words, this chapter is not intended to claim that every exchange should start with blocks without any restrictions. For instance, EXAA introduced blocks after one year when the market had somewhat matured. An interesting extension to this study could therefore be to explicitly address this issue.

Chapter 8

Clearing auctions with blocks: linear versus nonlinear pricing

8.1 Introduction

The previous three chapters discussed how exchanges treat blocks. As discussed in chapter 2, nonlinear pricing, as typically applied by power pools, is an alternative pricing approach for an auction with blocks. Most literature even prescribes nonlinear pricing for non-convex auctions, such as auctions with blocks. The main argument is trade efficiency.

Under nonlinear pricing, there is an hourly reference price but not all contracts are settled at that price, i.e. pricing is to a certain degree discriminatory. Therefore, there are many ways to implement this approach. The most extreme form is pay-as-bid, meaning that all accepted bids are settled at their price limit. The approaches used by power pools are however very different from pay-as-bid. Most trade is settled at hourly reference prices, but some contracts are settled at these prices in combination with a discriminatory payment, i.e. side payment. The use of side payments can even be minimized, as in Galiana et al. (2003).

Nonlinear pricing has been extensively studied by academics and practitioners and is also referred to as two-part tariff, augmented, or uplift pricing. Most of the literature is applied to power pools (e.g. Madrigal and Quintana, 2001; Motto and Galiana, 2002; Galiana et al., 2003), with the exception of O’Neill et al. (2006) who introduce a nonlinear pricing approach for auctions with blocks based on the ideas presented in O'Neill et al. (2005). Much less studied is linear pricing[40], the approach commonly used among exchanges. Exchanges impose hourly prices by rejecting blocks that actually want to trade at the determined prices without compensating them for this lost trade opportunity. The previous chapters have analyzed this approach. The contribution of this chapter is to evaluate whether exchanges should shift to nonlinear pricing. As argued in this chapter, the increase in gains from trade would be costly in terms of side payments that are necessary under nonlinear pricing.

First, the optimization models used to compare linear and nonlinear pricing when applied to auctions with blocks are discussed. Second, the approaches are compared qualitatively. Third, the linear and nonlinear pricing solutions to the auction problem with blocks are compared on the basis of representative scenarios introduced in chapter 5.

8.2 Models

The Mixed-Integer Linear Optimization Problem (4.5) to (4.16) (MILP2) introduced in chapter 5 formalizes the approach used by exchanges. Therefore MILP2 in this chapter models the solution under linear pricing.

As discussed in chapter 5, constraints (4.11) to (4.16) needed to be added to allow linear pricing. To model nonlinear pricing, these constraints can therefore be omitted. The Mixed-Integer Linear Optimization Problem (4.5) to (4.10) (MILP1) is used in this chapter to determine the solution in terms of quantities to the auction problem with blocks under nonlinear pricing. However, there is no unique set of prices to consequently settle this market.

In a convex auction, the shadow prices (λ_h) of the market clearing constraints (4.6) are market clearing in the sense that at those prices demand equates supply in all hours (Samuelson, 1952). For an auction with blocks this is not necessarily true. The MILP1 solution does not clear at λ_h, as gains from trade will not be maximized for all participants at these hourly prices, even though total gains from trade are maximized.

Participants can be accepted at a loss and others can be excluded even though they are in the money. Nonlinear pricing means that side payments will be used to compensate these participants for their losses and lost opportunities. In other words, also under nonlinear pricing, it is possible that blocks that want to trade at the determined market prices are rejected. The difference is that under nonlinear pricing they will be compensated for this lost opportunity to trade. Linear pricing yields PRBs, which are blocks that are in the money, rejected and not compensated.

Side payments are recovered from the accepted bids that are making a profit. It is important to underline that there is no unique way of doing this. To keep some generality, abstraction will be made of how the side payments are recovered when

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[40] In Motto and Galiana (2004a, 2004b and 2004c), a linear pricing approach is applied to power pools in which linear prices are imposed by rejecting generators that actually want to supply at the determined prices. This is very similar as the approach used by exchanges with linear hourly prices and blocks that can be excluded even though they are in the money (PRBs).

comparing nonlinear with linear pricing. Only the side payments are analyzed in this paper assuming that the hourly prices are taken as λ_h, which is the case in many of the approaches proposed for pools.

8.3 Qualitative comparison

In general, literature prescribes nonlinear pricing for non-convex markets such as auctions with blocks. The main argument is trade efficiency. As discussed in the previous chapters, exchanges impose linear prices, which can indeed imply smaller gains from trade. However, in Europe trade is mainly bilateral and exchanges are voluntary fine-tuning markets so that inefficient day-ahead auction trade does not necessarily imply that the wholesale market is inefficient. All depends of course on how inefficient linear pricing is. If the loss in gains from trade and the number of PRBs is large, the incentive to trade elsewhere is large so that in the limit the exchange is obsolete.

The question is whether exchanges with blocks would better apply nonlinear pricing. First of all, a change in price rules is costly in terms of reform costs. Second, making these price rules understandable to participants is also costly. In fact, nonlinear pricing approaches are often criticized for their complexity. Linear pricing is simpler as it yields prices at intersection of supply and demand curves, even though these curves are somewhat constructed (see chapter 5: blocks are included as price-taking hourly orders). Exchanges make optimal use of the property by publishing the aggregated curves.

Third, many alternative implementations of nonlinear pricing have been advocated and there is no consensus on which is best. Such a situation could result in an implementation benefiting certain parties at the cost of others.

Fourth, nonlinear pricing approaches have in common that trade is settled at hourly prices in combination with side payments. Participants can hedge against the day-ahead hourly price risk exposure with standard financial contracts (futures), but not against discriminatory charges that the exchange would need to use to recover side payments. As there is no counter part for these discriminatory payments, hedging them is expensive, i.e. personal insurance[41]. Again, all depends on how large these side payments are.

8.4 Quantitative comparison

Especially interesting in light of the argumentation of the previous section is to quantify the cost in terms of side payments to increase gains from trade by applying nonlinear pricing. The batch of scenarios introduced in chapter 5, is used to indicate the size of this ratio. Therefore, all scenarios have been solved under linear (MILP2) and nonlinear pricing (MILP1).

In this chapter, abstraction is made of computational complexity. Note however that the calculation time of MILP1 is substantially lower than that of MILP2. As

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[41] Note that this can partly explain why pools use nonlinear pricing approaches with less discriminatory payments than under a pay-as-bid approach and sometimes even (implicitly) minimize the use of side payments.

discussed in chapter 6, the solver calculation time for MILP2 is 4 minutes on average, with a maximum of 3.5 hours. The solver calculation time of MILP1 is only 0,6 seconds on average with a maximum of 1,4 seconds.

Figure 8-1 shows that the two approaches yield very similar hourly prices, as the daily averages are equal in up to 50% of the scenario days, and never deviate more than 10% in the sample.

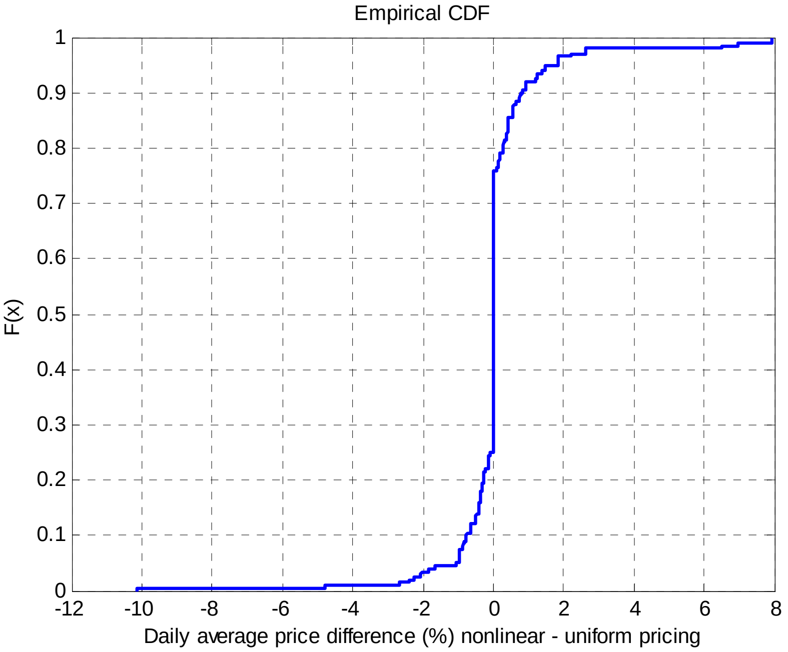

Figure 8-1: Cumulative Distribution Function (CDF) of the average day price difference nonlinear (λh) – uniform (ph) pricing

Figure 8-2 illustrates that the difference in gain from trade between the two approaches is small. In more than 50% of the scenarios the gain from trade is equal in both approaches, and the loss in terms of gain from trade of imposing linear prices is never more than 3697€ (max 0.05% of total surplus).

Figure 8-3 illustrates that the number of PRBs[42] can go up to 17, while in 75% of the scenarios there were no PRBs. On average there is 1 PRB per day, but the likelihood of a block being paradoxically rejected is very low (<0.1%).

Figure 8-4 illustrates that to avoid PRBs and to maximize gain from trade in all scenarios, side payments are necessary in up to 60% of the scenarios. In 10% of the scenarios side payments from 5000€ to 47498€ (max 0.64% of total surplus) have to

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[42] As discussed in section 5.5.1, only PRBs that are actually loosing money are counted here. PRBs with a price limit equal to the average market price are not counted, as nonlinear pricing is not a solution for these blocks.

be made. Note that side payments in the sample are only made to block bids[43], with the average payment being 502€.

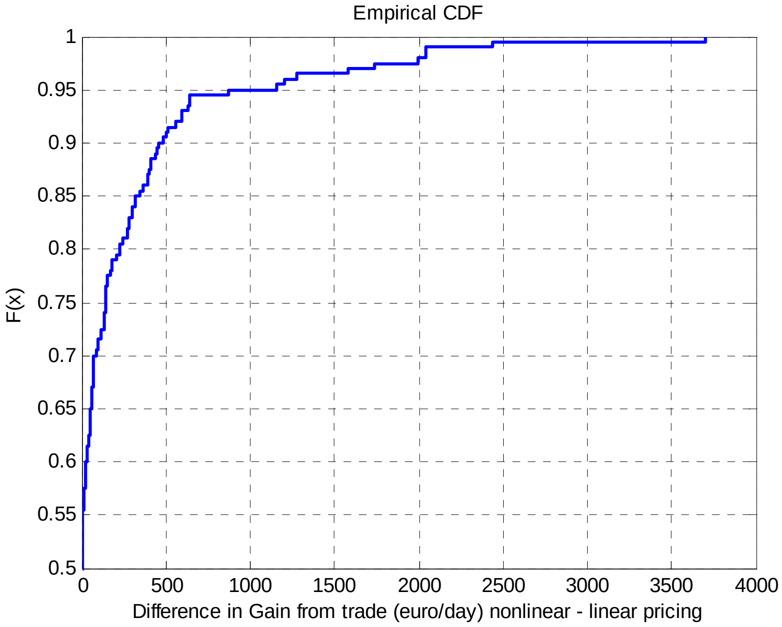

Figure 8-2: Cumulative Distribution Function (CDF) difference gain from trade nonlinear – uniform pricing

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[43] This is consistent with the theory presented in [6], where it is shown that side payments can also be determined as the shadow prices of the constraints that cause non-convexities, such as the indivisibility constraint of block bids.

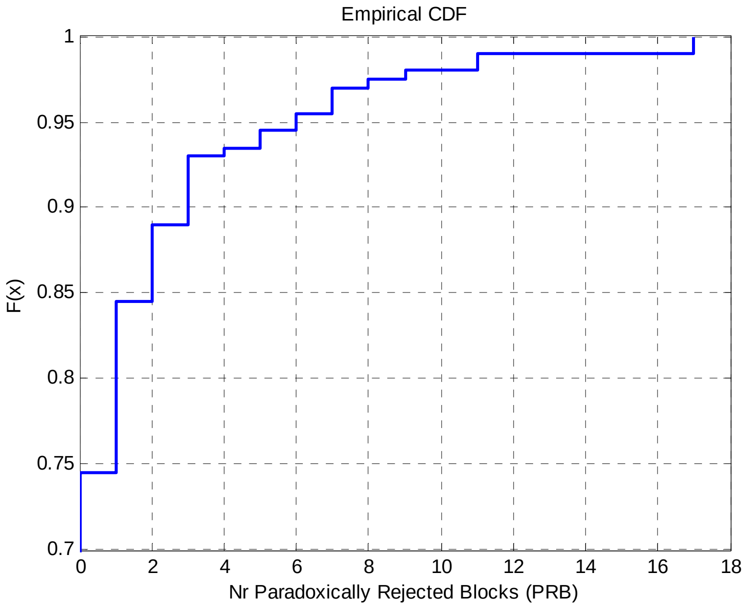

Figure 8-3: Cumulative Distribution Function (CDF) Paradoxically Rejected Blocks (PRB) under uniform pricing

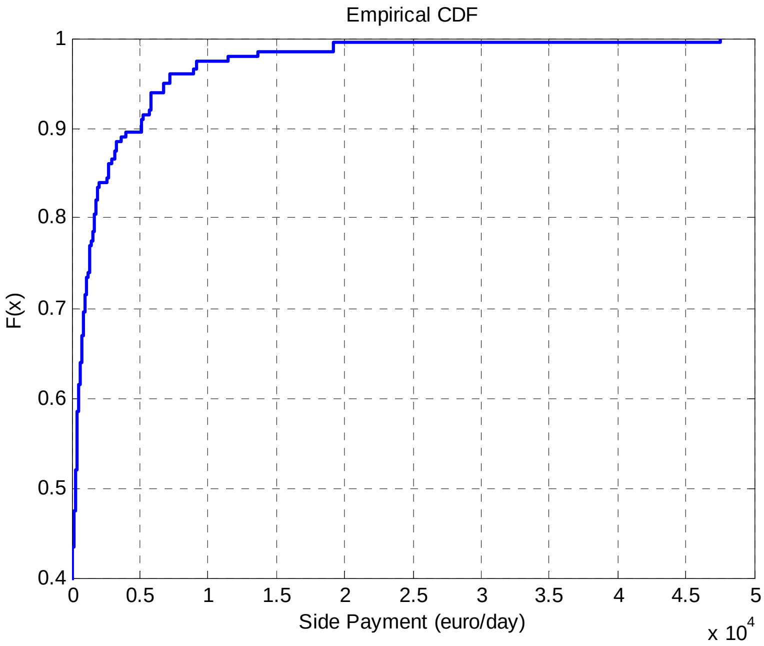

Figure 8-4: Cumulative Distribution Function (CDF) side payments under nonlinear pricing

Relative to total surplus, both side payments and the increase in gains from trade from applying nonlinear pricing are small. In comparison, a total of 317393€ is paid in side payments, which is 8,7465 times more than the sum of the differences in gains from trade.

The ratio side payments over difference in gain from trade is an interesting statistic to look at per scenario. In scenarios with a difference in gain from trade, the ratio is finite and can be plotted as illustrated in Figure 8-5. Some of the values are off the graph to increase the visibility of the other values, but the maximum value of the ratio is 1098.

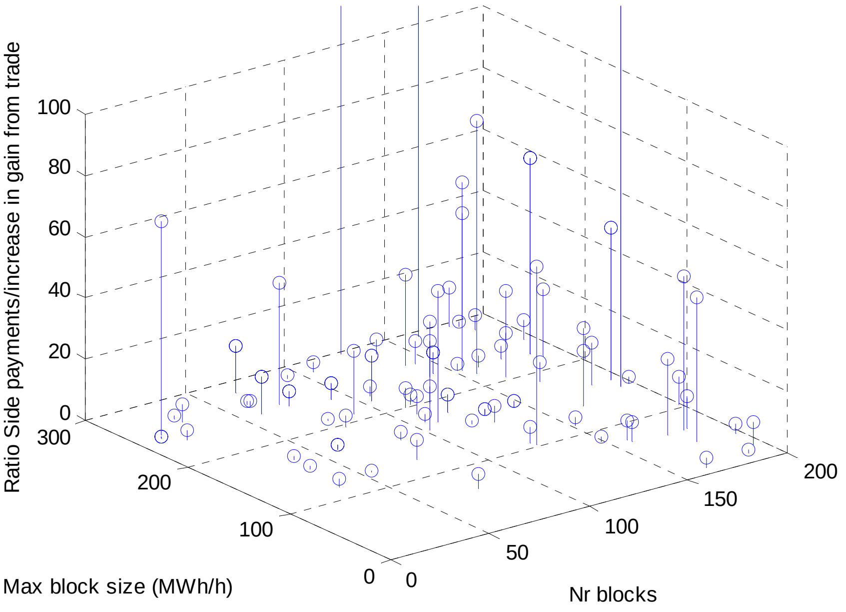

Figure 8-5: Sensitivities of the ratio side payments nonlinear pricing over difference in gain from trade nonlinear – linear pricing

In Figure 8-5 only 9 of the 97 scenarios yield a ratio smaller than 1, meaning that in general for every € won in terms of gains from trade, several € side payments are necessary. Note that in 31 scenarios, side payments were made; even though this did not increase gains form trade.

8.5 Conclusions

The European exchanges apply linear pricing, while most literature prescribes nonlinear pricing for non-convex auctions. In this chapter, it has been argued that in the case of exchanges the drawbacks of linear pricing are less severe, while there are clear advantages.

Based on representative scenarios it has been indicated that trade in the voluntary auctions organized by exchanges is not fully efficient. However, inefficient day-ahead auction trade does not necessarily lead to an inefficient dispatch in a market with several voluntary wholesale markets. Furthermore, a shift to nonlinear pricing would be costly in comparison with the possible gains from trade.

Besides the obvious costs caused by the reforms, it has been argued that there is also a cost linked to the use of side payments. Due to side payments, the day-ahead price risk cannot be fully hedged with standard future contracts, which are settled against the hourly reference prices. Furthermore, nonlinear pricing is often perceived as complex and not always well understood. Finally, the analysis performed in this chapter indicates that for every € won in terms of gains from trade, several € side payments are necessary. This result holds on average but also in the individual scenarios, with a few exceptions.

Note that this work is also of relevance for other non-convex markets, but it is not intended to claim that all these markets should apply linear pricing. For instance, inefficient trade in a mandatory pool is likely to result in an inefficient dispatch, meaning that the drawbacks of linear pricing weigh much heavier in a power pool. Still, an interesting extension to this work could be to calculate the above-mentioned ratio of side payments over increase in gains from trade for representative power pool scenarios.

Chapter 9

Market coupling algorithm: centralized versus decentralized block order selection

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9.1 Introduction

Most European countries have a power exchange. Traders acquire cross-border transfer capacities to arbitrate between the exchanges. These capacities are auctioned independently per border and on different time scales. Alternatively, the Scandinavian exchange Nord Pool optimizes the clearing of orders introduced in Norway, Sweden, Denmark and Finland (partly also Germany). This implies that Nord Pool implicitly auctions all available capacities on the internal interconnections between these countries. If the network allows it, Nord Pool therefore determines a single price for all zones; otherwise the market is split into predefined price zones, i.e. market splitting. Market splitting, as currently implemented in Nord Pool, is however not flow-based.

The association of European Transmission System Operators (ETSO) has long been promoting a coordinated and flow based approach for the allocation of capacities. The association of European power exchanges (EUROPEX) added the idea of a decentralized approach. Instead of having one exchange, the idea is to couple existing exchanges without fully harmonizing them. In the EUROPEX proposal (2003), the idea is concretized by a scheme in which exchanges share information on net-export curves (NEC). This scheme was consequently also the basis of a joint statement by ETSO and Europex (2004). Most of these proposals are political and do not include an implementation or model. For instance, Ehrenmann and Smeers (2005) have raised concerns on the implementation of network constraints in some of these proposals.

NECs contain enough information about hourly orders to have an optimal coupling[44]. However, most exchanges in Europe also have block orders. As discussed in previous chapters, dealing with blocks is challenging. To accommodate for blocks, ETSO and Europex (2004) propose to exchange NECs in several iterations. This implies that block order selection is decentralized. The contribution of this paper resides in discussing the impact of decentralized block order selection on the performance of the market-coupling algorithm.

In France, Belgium and the Netherlands, an algorithm with decentralized block selection has been developed to couple the exchanges Powernext, Belpex and APX. The three national regulators are currently validating the chosen approach. One of the concerns they have raised is on the extendibility of the approach to more markets (CRE, CREG and DTE, 2005). Decentralized block order selection might also be an issue in the German proposal 'Open Market Coupling' (OMC). The OMC proposal was for instance presented by EEX at the mini-forums on congestion management (EEX, 2005) and is currently being evaluated by the German regulator. The OMC proposal addresses the fact that not all countries in Europe have an exchange, while some have more than one. The proposed approach is to let exchanges and other interested parties bid on the capacities, which are then allocated by an open auction office. The proposal does however not discuss the information that is exchanged during the bidding process.

First, the concept of decentralized block order selection is explained. Second, the impact on performance is discussed. Finally, the difference in performance is numerically compared for representative scenarios using a simple algorithm with decentralized and centralized block order selection.

9.2 Decentralized block order selection

To accommodate for blocks, ETSO and Europex (2004) propose to exchange NECs in several iterations. NECs express per location per hour how the price would evolve if there were import or export at that location. As discussed in the proposal, NECs can be derived straightforwardly from the aggregated supply and demand curves[45]. This is however only true for a given block set. Therefore, the proposal to exchange NECs in several iterations to deal with blocks implies that the auction problem is decomposed into a coordination module and a block selector (see chapter 5).

In fact, the problem is even further decomposed as every exchange produces a NEC, meaning that block selection is done decentralized as illustrated in Figure 9-1.

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[44] This is shown in Meeus et al. (2005c).

[45] Which has also been illustrated in chapter 4.

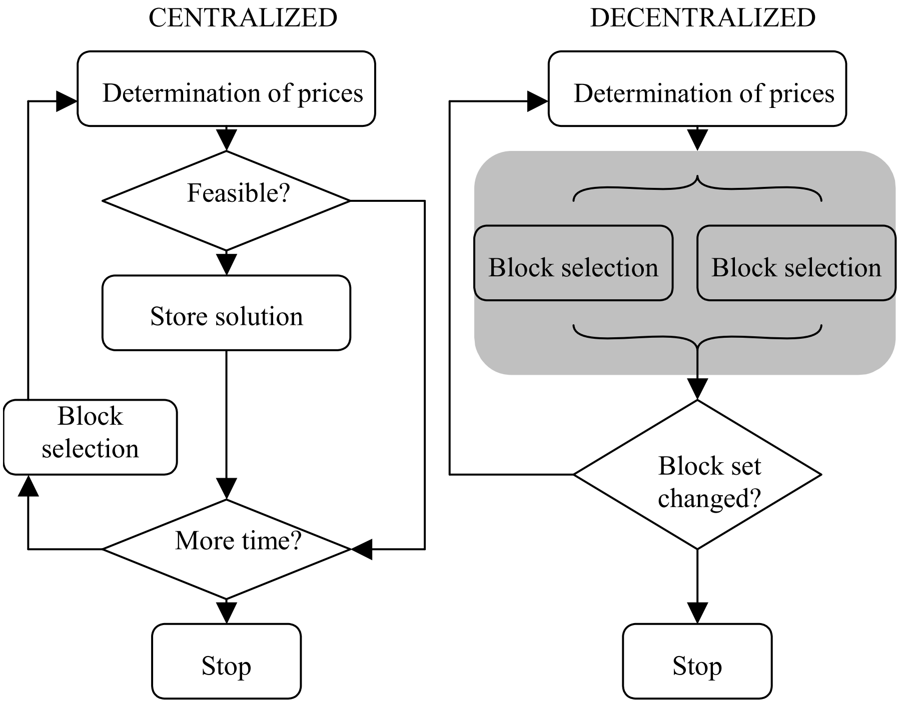

Figure 9-1: Scheme with centralized versus decentralized block order selection, with gray area showing the decentralized modules of the different exchanges

In a scheme with decentralized block selection, block order information is decentralized so that the number of possible solutions is not known centrally and enumeration[46] is not possible.

Consider the two period example of chapter 5 with one supply block (section 5.2, Example 1). There are only two possible solutions and the only feasible solution is to reject the block. Imagine that every exchange would simply respond to prices by selecting all blocks that want to trade at the current prices. Assuming that the procedure starts by putting the block in, the following would happen in Example 1:

- Iteration 1: the supply block is accepted meaning that the average price is 22,5 €/MWh. When this is communicated to the exchange, it would respond by putting the block out and producing a NEC without the block.
- Iteration 2: the block is rejected meaning that the average price is 90 €/MWh. When this is communicated to the exchange, it would respond by putting the blocks in and producing a new NEC.

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[46] Obviously, solving the auction problem with available commercial optimization software is also excluded.

- Iteration 3 = Iteration 1, etc.

As shown in Figure 9-1, the procedure can only be stopped if the NECs do not change from one iteration to the other, i.e. the same blocks are selected as in the last iteration. This means that convergence needs to be guaranteed by the decentralized block selector. In principle also the solution found with decentralized block selection can be stored and the process repeated, but it would not be possible to choose between several feasible solutions. Blocks are included in NECs as price taking orders so that gain from trade or the number of PRBs is not known centrally. As a consequence, even if enough time is available to try all block combinations, the scheme with decentralized block selection cannot guarantee to find the optimal solution.

9.3 Impact on performance

Clearly, a scheme with centralized or decentralized block selection can be implemented in many ways so that it becomes difficult to compare them, also because the comparison will be sensitive to the assumed available calculation time and power. To have some indication of their relative performance, simple algorithms can be used. The idea is that the performance of these simple algorithms is a lower bound for the performance of more specialized algorithms and that the relative performance of the lower bounds gives an indication about the relative performance of specialized algorithms. The lower bound algorithms respectively LBAC and LBAD are introduced and discussed in what follows. Figure 9-2 shows both flow diagrams.

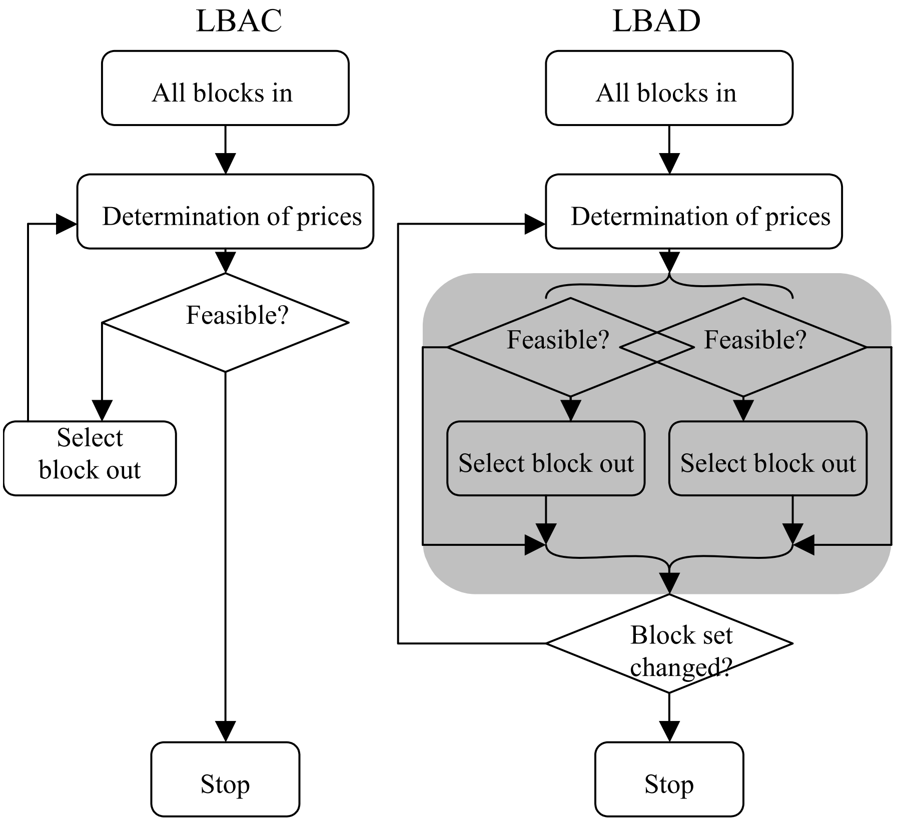

Figure 9-2: LBAC-LBAD flow diagram, with gray area showing the decentralized modules run by the different exchanges

Note that both algorithms are an extension to multiple markets of LBA, the simple algorithm introduced in chapter 6 (section 6.3). Both algorithms initialize by putting all blocks in and every iteration step a block is selected to go out. Blocks cannot come back and the algorithm stops in both cases when a feasible solution is found. The difference is that in LBAD a block is selected to go out per exchange (per location), as block selection is decentralized.

9.4 Simulations

The goal of the simulations is to asses, based on representative scenarios, if LBAC and LBAD exhibit significant outcome difference on average. Furthermore, it is to verify if the difference in performance significantly increases with the number of markets (or zones to be coupled).

The scenarios are constructed in a similar way as the batch of scenarios used in previous chapters (chapter 5 introduced the batch of representative scenarios). The difference is that in these simulations hourly orders for different locations or markets are needed. APX curves of different days are used for different markets. Table 9-1 illustrates the days that have been used.

Table 9-1: Days used for curves of different locations in the simulations[47]

Date (DD/MM/YY)	Average price (€/MWh)	Maximum price (€/MWh)	Total traded volume (MWh)
25/03/05	39	60	46373
03/04/05	26	50	40843
07/05/05	32	42	42964
25/05/05	43	80	35119

For the scenarios that are discussed in what follows, the minimum number of blocks added to a scenario is 50 times the number of locations in a scenario, while the maximum is 100 times the number of locations in a scenario. In other words, the results presented here are for a conservatively low number of blocks.

Blocks are added to the scenarios as follows:

- Every block is randomly one of the 10 types traded on Powernext and has 60% probability of being a supply block order and only 40% probability of being a demand block order.
- Block size (MWh/h): random integer between 1 and 150. Note that blocks are taken smaller in these scenarios, which is more realistic as most exchanges restrict the size of blocks (as discussed in chapter 7).
- Block price limit (€/MWh) is a smaller than 10% random deviation from the average price of the day representing the location where the block is introduced. In other words, the prices limits are close to what would be the price when no blocks were included.

2 markets increasingly interconnected

In the extreme case when there is no interconnection capacity, prices are decoupled and the problem with blocks could actually be solved separately for the different markets. However, the more network that needs to be allocated, the more prices are coupled, the more LBAC outperforms LBAD (Figure 9-3).

Figure 9-3 illustrates for two markets that the more these markets are interconnected the more LBAC outperforms LBAD both in terms of Gain from Trade (GfT) and number of PRBs. Note that both LBAC and LBAD perform better as more interconnection capacity is available, but the increase in performance of LBAC is significantly greater.

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[47] Available at http://www.apxgroup.com.

The average differences in GfT for 2 locations is of the order of 450€ per day, which is not spectacular as such, but is significant on an annual basis. A simple extrapolation to 365 days yields a cumulative difference of 164250 € per year.

Furthermore, the difference in terms of PRB is of the order of one. On average, LBAD yields 10 to 70% more PRBs than LBAD for increasing interconnection capacity.

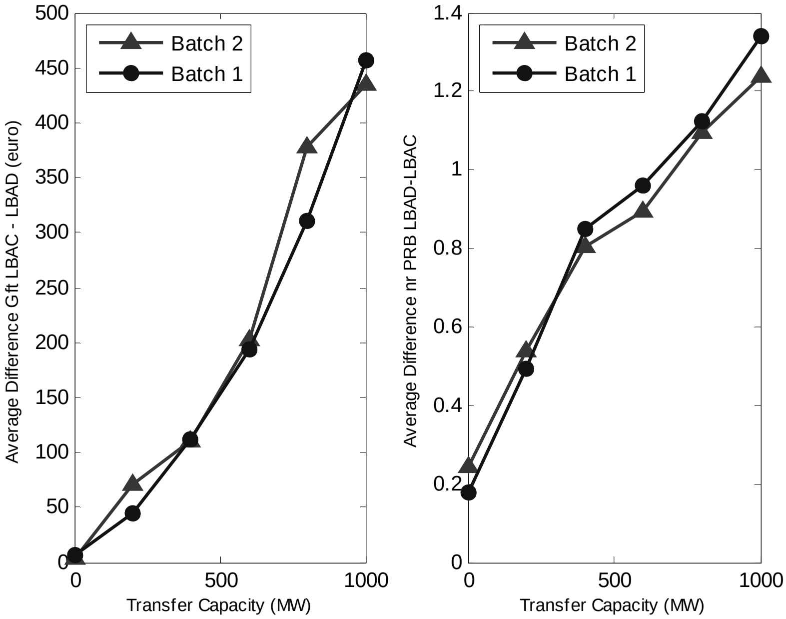

Figure 9-3: Relative performance lower bounds for 2 markets increasingly interconnected

Increasing number of markets interconnected by copper plate

Figure 9-4 illustrates that on average the difference in performance between LBAC and LBAD increases, as the number of locations increases and more blocks have to be dealt with. For 2 to 4 markets, 200 scenarios have been run assuming a copper plate network.

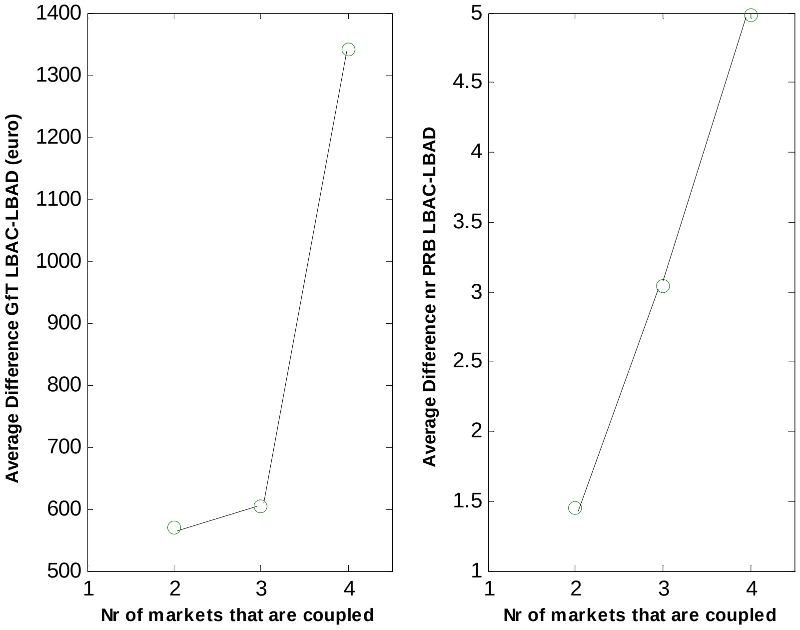

Figure 9-4: Relative performance lower bounds for increasing number of markets

9.5 Conclusions

In relatively small-scale scenarios with a small number of blocks, all potential solutions could be enumerated within the time available to the exchange and the best solution selected. If the selection of block orders is decentralized, enumeration is however not possible. Neither is it possible to use a single optimization model. It is not even possible to compare different solutions. Decentralized block order selection is therefore clearly inferior if there is no binding time constraint.

In realistic scenarios, a binding time constraint is however likely as not much time is available to the exchanges and the problem to be solved is computational intractable. To find a good but not necessarily optimal solution fast, it is common among exchanges in Europe to decompose the auction problem into a block selector and a coordination module that determines prices (see also chapter 5). However, if this block selector is decentralized, the auction problem is even further decomposed, i.e. different modules are selecting blocks without direct communication or coordination.

Representative scenarios have been solved with a very simple algorithm with centralized and with decentralized block order selection. The relative performance of these lower bound algorithms indicates that decentralizing the selection of block orders has a negative impact on performance, which can increase as the market develops and more markets are coupled.

Decentralized market coupling could replace the system in place throughout Europe with separate explicit auctions for interconnection capacity on the borders. As discussed in this chapter, the decentralized approach is however not the best way to treat block orders. In other words, the decentralized system with implicit arbitrage is imperfect, but also the current system with explicit arbitrage has its imperfections (see discussion in chapter 2). This chapter is therefore not intended to claim that decentralized market coupling is better or worse than the current system with explicit auctions.

Chapter 10

Conclusions and Future Research

10.1 Overview

In what follows, the main conclusions are outlined, indicating potential extensions to this study. Finally, some thoughts on future research are provided.

10.2 Main conclusions

Most power exchanges in Europe are platforms where market parties can exchange electric energy within the control zone of a TSO, which is often confined within national borders. Trade is anonymous and traders do not have to worry about the insolvency of their counter party. The exchange itself is counter-party for all transaction. Contracts that can be traded on the exchanges are standardized and are settled without discussion or negotiation, according to transparent and simple rules.

Increasingly, electric energy auctions are also used to organize trade between TSO control zones. This allows for a better clearing of orders introduced at different exchanges. The changing context implies new challenges for the exchanges, but also renews the discussion on how former challenges have been addressed.

The auction problem has been modeled as a constrained optimization problem and alternative solutions have been analyzed. This has provided valuable insights for the implementation and functioning of exchanges. In what follows, respectively the main conclusions on the auction design (chapter 2), the treatment of network constraints (chapters 3 and 4), block orders (chapters 5, 6, 7 and 8) and political constraints (chapter 9) are discussed.

10.2.1 Auction design

The three main design characteristics of electric energy auctions are related to participation, non-convexities and network constraints. From this perspective, auctions organized by exchanges in Europe are different from auctions elsewhere.

First, exchanges are voluntary, while power pools are mandatory wholesale markets. Note that this is important for the argumentation that follows. It means that inefficient trade in these auctions does not necessarily lead to inefficient wholesale trade and inefficient dispatch, as there are many trading alternatives. In other words, some of the claims made in this study are not applicable to power pools.

Second, exchanges have in common with power pools that they are non-convex auctions. However, they deal differently with non-convexities:

- Exchanges have block orders instead of the more flexible multi-part orders that can be found on pools. Pools allow participants to express fixed costs, variable costs and all kind of technical constraints. Exchanges only have hourly orders that are simple price-quantity orders and block orders. Block orders are for multiple hours and have a fill-or-kill constraint. The auction with blocks is not incentive compatible. E.g. a generator will have to fix volume to have revenue certainty, even though he could recover his costs at several output levels and prices. However, the use of blocks is so common that it has been taken as given in this study.

- Exchanges do not actually clear their auctions. The prices they determine do not necessarily equalize demand and supply, but the exchanges force the equality. More specifically, they exclude blocks that are in the money without compensating them for this lost trade opportunity[48], i.e. they apply linear instead of nonlinear pricing. Even though linear pricing is common among exchanges, the alternative has been analyzed. The conclusions of this analysis are discussed in the main conclusions on the auction problem with block orders.

An interesting extension could be to study the inclusion of other products on the exchanges. Block orders are characterized by a fixed quantity that is introduced for several hours with an average price limit. The most obvious extension could be to allow traders to submit an average price for ‘profiles’, instead of fixed quantities for multiple hours. Other product extensions could be inspired by the multi-part orders of power pools. Note however that in contrast with power pools, exchanges allow traders to introduce these products at the demand as well as at the supply side. Therefore, adding more flexible multi-part orders to the clearing of exchanges is computationally more difficult than in the case of power pools.

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[48] These blocks have been referred to as Paradoxically Rejected Blocks (PRB) throughout this text.

Third, in contrast with pools most exchanges do not take into account network constraints. However, exchanges are increasingly involved in cross-border trade, which means that they also need to deal with network constraints.

10.2.2 Network constraints

Transmission network constraints are not ordinary transport constraints. Power flow is economically uncontrollable, meaning that flows are distributed over the network according to the relative impedance of the available paths from generation to load. When imposed on a market, transmission network constraints are generally simplified into linear constraints, meaning that the auction problem with these constraints is an easy to solve linear optimization problem.

This study has however identified two problems with this well-known problem when applied to exchanges. Due to the discontinuities in the aggregated curves of the exchanges, the problem does not uniquely determine prices and quantities. As illustrated, this means that the software used to solve the problem has a significant impact on the market outcome.

The possible sets of prices to choose from equally provide efficient locational signals to demand and supply. Furthermore, this feasible set can be formulated as a set of linear equations, so that the choice can be formulated as a separate optimization problem. This formulation needs an objective function to decide on prices. Minimizing the cost of congestion has been proposed, arguing that congestion revenue is not always used efficiently.

Less clear is the choice between possible sets of quantities. As illustrated, both flow and traded volume, besides gains from trade, are necessary to uniquely determine quantities. It can be argued that both more volume and less flow increase trade efficiency, but how to weigh these objectives is arguable.

10.2.3 Block orders

Blocks are important for traders and exchanges. With blocks, traders can better express their multi-period cost structures than with hourly orders. For exchanges it means that they can attract more volume in competition with bilateral markets, where contracts are as flexible as parties can agree upon.

To study the auction problem with blocks, it has been modeled as a constrained optimization problem and alternative solutions have been analyzed in a batch of representative scenarios.

Computational complexity

First, the computational complexity of the problem has been analyzed.

- The computational complexity of the auction problem with blocks is such that heuristics need to be used. For the simulations presented in this text, the problem has been modeled as a Mixed Integer Linear Problem (MILP). Note however that a flat hourly order system has been assumed for the simulations, which is not used by all exchanges. As discussed, some exchanges have a more difficult problem to solve than the one modeled in the simulations.

- The complexity of the model has been discussed based on the calculation time of the software used to solve the problem in representative scenarios. Against expectations, the number of blocks was not determinative for this calculation time. The constraints necessary to allow linear pricing have been identified as the major source of complexity. Without these constraints, the problem could be solved within 1,4 seconds for all scenarios in the sample. If the constraints were added, scenarios were found that did not yield a solution within the day.

- All exchanges decompose the problem into a block selector and a coordination module that determines the prices for a fixed block set. Such a decomposition of the problem allows them to find a feasible but not necessarily optimal solution fast. The heuristic procedures used in practice are not publicly available so that they could not be evaluated. The optimal solution has therefore been compared with the solution found by a simple algorithm based on the decomposition as applied by exchanges. The results indicate that there is money to be made with designing a good performing heuristic. The heuristic algorithms should therefore be carefully validated.

An interesting extension could be to add network constraints to the model of the auction problem with blocks. As mentioned previously, network constraints are imposed on a market simply by adding a set of linear equations. However, the price properties of the auction problem with network constraints (Locational Marginal Pricing, as discussed in chapter 4) can change when blocks are added. To keep these properties, the optimality conditions of the problem with network constraints but without blocks will have to be added to the model. Furthermore, all exchanges solve the problem with the same decomposition. Most exchanges do however not yet take into account network constraints. Perhaps there is a superior alternative approach when also network constraints have to be taken into account.

Block order restrictions

Second, block order restrictions have been addressed.

- The attractiveness of a block in comparison with hourly orders comes from its indivisible and multi-period character. However, to clear their market, exchanges exclude blocks that are in the money without compensating them for this lost trade opportunity, which makes blocks less attractive for traders. The question could therefore be raised whether restricting the use of blocks reduces the problem of PRBs[49]. This could partly explain why all exchanges have restrictions on the size (MWh/h) or the type (span in terms of hours) or the number of blocks that can be introduced per participant per day.

- A sensitivity analysis has been performed on scenarios with and without a type restriction, with a total number of blocks going from 1 to 200 and with maximum block sizes going from 10 to 300MWh/h. Against expectations,

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[49] A trader introducing such a block is expecting to be accepted based on the determined prices, while he is not. When faced with this problem, traders possibly file a complaint and perhaps also start distrusting the product and even the exchange.

blocks are not more likely paradoxically rejected if the total number of blocks in the scenario is larger, nor if also large blocks or many different types of blocks are included. It has therefore been concluded that exchanges over restrict the use of blocks. It is in their own benefit and in the benefit of traders to omit these restrictions, as these restrictions only reduce the volumes traded on exchanges and oblige traders to find alternatives.

- Small blocks are less likely to be paradoxically rejected. However, this in itself is not a reason to restrict all traders to using small blocks, as traders submitting small blocks are not affected by the fact that other traders are submitting larger blocks. Note also that overall the likelihood of a block being paradoxically rejected is rather low (average of 4% in the sample).

Note that abstraction of computational complexity has been made in the above analysis. Furthermore, the situation with many blocks and just a few hourly orders has not explicitly been addressed. In other words, this chapter is not intended to claim that every exchange should start with blocks without any restrictions. For instance, EXAA did not introduce blocks from start, but after one year when the market had somewhat matured. An interesting extension to this study could therefore be to explicitly address this issue.

Linear versus nonlinear pricing

Third, the pricing approach has been questioned.

- As mentioned previously, exchanges have in common with power pools that they are non-convex auctions. However, they deal differently with non-convexities. Exchanges have blocks, while power pools have more flexible multi-part orders. Furthermore, exchanges do not actually clear their auctions. They exclude blocks that are in the money without compensating them for this lost trade opportunity, i.e. they apply linear instead of nonlinear pricing. Nonlinear pricing as typically applied by pools is also prescribed by most literature for auctions with non-convexities. O'Neill et al. (2006) propose a nonlinear pricing approach for auctions with blocks.

- The main argument in favor of nonlinear as opposed to linear pricing is trade efficiency. However, inefficient day-ahead auction trade does not necessarily lead to an inefficient dispatch in a market system with several voluntary wholesale markets.

- The main drawback of nonlinear pricing is the use of discriminatory payments. Under nonlinear pricing, there are hourly prices but there are also side payments to compensate participants for losses or lost trading opportunities. There are many ways to recover these payments from participants that are making a profit, but all imply that these participants are exposed to discriminatory charges. The size of these so-called side payments is an indication for this exposure. An exposure to discriminatory charges is a problem for traders as it is expensive to hedge, i.e. personal insurance. Furthermore, a shift from linear to nonlinear pricing in Europe would imply reform costs.

- In other words, there is a clear advantage to linear pricing (no discriminatory charges), while the disadvantage (trade inefficiency) is less a problem because the exchanges are voluntary markets. Furthermore, the linear and nonlinear pricing solutions have been compared in representative scenarios. Indeed, linear pricing is slightly less efficient, but the results indicates that for every € won in terms of gains from trade, several € side payments are necessary under nonlinear pricing. This results holds on average but also in the individual scenarios, with a few exceptions.

Note that in a mandatory pool, inefficient trade is more problematic meaning that the main drawback of linear pricing weighs much heavier. Still, an interesting extension to this work could be to calculate the above-mentioned ratio of side payments over increase in gains from trade for representative power pool scenarios.

10.2.4 Political constraints

The association of European Transmission System Operators (ETSO) has long been promoting a coordinated and flow based approach for the allocation of capacities. The association of European power exchanges (EUROPEX) added the idea of a decentralized approach. Instead of having one exchange, the idea is to couple existing exchanges without fully harmonizing them.

A decentralized approach can be interesting from a regulatory and political point of view. However, the proposed decentralized scheme implies that block order selection is decentralized. As explained previously, it is common among exchanges in Europe to decompose the auction problem into a block selector and a coordination module that determines prices. If this block selector is decentralized, the auction problem is further decomposed, i.e. different modules are selecting blocks without direct communication or coordination.

If the selection of block orders is decentralized, enumeration of all possible solutions is not possible. Neither is it possible to use a single optimization model. It is not even possible to compare different solutions. Furthermore, representative scenarios have been solved with a very simple algorithm with centralized and with decentralized block order selection. The relative performance of these lower bound algorithms indicates that decentralizing the selection of block orders has a negative impact on performance, which can increase as the market develops and more markets are coupled.

Decentralized market coupling could replace the system in place throughout Europe with separate explicit auctions for interconnection capacity on the borders. As discussed in this chapter, the decentralized approach is however not the best way to treat block orders. In other words, the decentralized system with implicit arbitrage is imperfect, but also the current system with explicit arbitrage has its imperfections. The analysis is therefore not intended to claim that decentralized market coupling is better or worse than the current system with explicit auctions.

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10.3 Looking ahead

The current market is built on the network foundations that resulted from a pre-liberalized context. In the liberalized context, new opportunities have emerged for old technologies and new promising technologies are under development. The grid of the future will very probably be larger, more flexible, more controllable and automated. The challenge facing network operators today is to invest in the network in this new context in order to be more independent from generation for system operation, such as for reactive power support and other ancillary services. Consequently, the challenge is of course to optimally use the new operational opportunities created by these investments.

First, the investments will improve market facilitation by making the network more available to the market. One of the advantages could be that more network capacity can be made available for wholesale trade, ultimately leading to a single European electric energy price for most of the time. Second, it seems unavoidable that market organization will also change to optimally take advantage of the newly created opportunities, such as controllable flow.

In other words, the challenge will be to develop market mechanisms that besides using the network also control it to the extent that it is considered economically opportune. The coupling of electric energy auctions organized by exchanges takes into account simplified network constraints, assuming that flow factors and available network capacities are a-priori fixed by the TSOs. In the future, control over flow factors, available capacities and interdependencies could for instance be taken into account in the clearing algorithms of electric energy auctions. Naturally, this also implies new challenges for auction trading platform design.

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Curriculum Vitae

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