MŰEGYETEM 1782

Budapest University of Technology and Economics

Faculty of Electrical Engineering and Informatics

Department of Electric Power Engineering

Ádám Sleisz

Integrated Clearing Models for Innovative Order Types on the All-European Power Exchange

Theses

SUPERVISOR

Dr. Dávid Raisz

2018

1 Introduction

1.1 Outline of the topic

Actors in the power sector – just like almost any other enterprise in the economy – are dependent on financial capital. Since the amount of capital is limited, its appropriate allocation is of primary importance: the entire study of market rules and designs is dedicated to find the best preforming trading procedures, organizational structures and regulation policies for this task.

Electricity markets in particular have been providing a rich and important field of research projects for the last two decades. They constitute an integral part of the worldwide energy sector liberalization, a process which aims at the increased economic efficiency of this critical sector as well as the simultaneous sustainment of adequate technical reliability.

The emergence and subsequent spread of day-ahead power exchanges (PXs) is a result of this endeavor. These are public, centralized trading platforms on which electric energy is traded in an organized manner. Every PX has certain specifications about time schedule, products, coupling options, bid structures, etc., these characteristics can make their actual implementation substantially different.

An ongoing large project of the European Union is to create an Internal Energy Market [1]. In this context, a unified PX is constructed along with the corresponding single clearing algorithm called EUPHEMIA [2]. However, the implementation of the original proposal is not trivial because several innovative elements and also components from PX algorithms of different member states are supposed to be applied together.

The dissertation presents computationally efficient optimization models to answer some of the most challenging questions i.e. those about the implementation of complex supply order clearing and unified purchase prices.

1.2 Motivation: the need of integrated models

An important factor in the development and fast spread of applied optimization is the possibility to separate problem formulations from solution algorithms. Optimization problems emerge in many scientific disciplines and encompass a very diverse set of special and often complicated concepts. On the other hand, there are generic solution techniques for several distinct categories of problems which are continuously subjected to innovative ideas and research projects of their own (e.g. [3], [4] and [5]).

The separation of model formulations from solution methods is advantageous because researchers, scientific and industrial experts (e.g. economists, engineers, sociologists, etc.) who describe mathematical models do not have to know and implement every algorithmic detail of the solution search. Using generic solution algorithms, designers and analysts of problem formulations can easily conduct experiments and compare results between different variants and versions of their models. In order to use these routines, models must be converted into the compact standard form of one of the available problem classes.

At the same time, mathematicians who provide the solution methods usually do not have to be trained in the field of every application. They can compare any model with other instances of the same problem class using specific attributes and performance metrics without getting involved in the exact interpretation of constraints and variables.

The division of knowledge and labor is particularly beneficial for industrial applications because it means that several proficient solver software are available on the market. Since state-of-the-art technology and experience in a wide range of computational applications are built into these solvers, they can usually provide fast results and robust performance.

The clearing problem of electricity markets is one of the applications for which the described approach is usually abandoned. The most frequent way non-convex elements are handled during the clearing process is based on their removal from the core model formulation. Generic algorithms are used to solve this simplified core model – the Welfare Maximization Problem in the case of EUPHEMIA [2] – while its results are utilized in problem-specific heuristic techniques. These techniques – collectively called the Price Determination Subproblem in EUPHEMIA [2] – are essentially designed to correct violations of the externalized model conditions and find feasible solutions.

The external coercion of feasibility often infers a significant reduction in solution quality. As a result of this algorithm structure, global optimization can only be implemented as an iterative process in which search routines for good objective values and feasible solutions are launched alternately. There is no point in the process when solution quality and feasibility are considered simultaneously.

Using this approach, experimental modifications in the PX design can easily lead to models that are unsolvable or extremely hard for the actual solution method. On the other hand, if both the model and the solution algorithm are modified, then no easy way remains to compare different versions. The problem-specific nature of the solver routine means that the knowledge of applied solution methods in different fields is almost useless because not just the procedural steps are different but basic performance metrics e.g. standard measures and proofs of optimality are also missing.

COSMOS [6] included the first PX clearing model in Europe that is standardized in the above described sense. It is formalized as a single convex Mixed Integer Quadratic Problem (MIQP), a category that can be handled by generic solution algorithms. The advantageous features of standard models contribute to its ongoing successful use in Europe.

The market model of EUPHEMIA is an extended variant of the COSMOS formulation. If the extensions could be inserted into a similar standard convex MIQP, the above mentioned benefits would be accessible. The dissertation presents the attempt to achieve this goal for critical elements in EUPHEMIA.

2 Theses

2.1 Thesis 1

Complicated properties of power generation have been one of the most challenging issues in electricity market design since the appearance of the subject [7]. The expenses of building, operating, maintaining and decommissioning power plants are ideally handled by market forces meaning that various fixed and variable costs are associated with every unit of supplied energy. On the other hand, several technical constraints (e.g. minimal operating loads and load gradient limitations) are also present which can make daily electricity trading more complex than the case of most other commodities.

The main hindrance arising from these considerations is that the overall economic model of power plants is generally non-convex in nature, and non-convex elements make practical PX clearing problems substantially harder to solve. Thus, the introduction of non-convexities is unavoidable to provide feasible clearing results for suppliers but the computational burden evoked by them must be reduced as much as possible. This trade-off can be more or less assessed by careful formulation of supply order types such as different kinds of supply block orders.

Complex orders offer an alternative approach in this endeavor. They have their potentially non-convex element – the so-called Minimum Income Condition (MIC) – and can provide a sensible improvement in the economic model of power supply compared to block orders.

> (**Thesis 1**) *A new formulation has been found for complex orders with Minimum Income Conditions on the officially proposed all-European day-ahead power exchange which can be used to incorporate these orders into the European market clearing framework without special algorithmic solution procedures. Exploiting the recognized effects of marginal pricing logic on bid incomes, the new mathematical model decomposes the inherently non-convex income calculation into convex cases. The resulting clearing model can be solved using generic optimization software enhancing the analysis options and practical applicability of the Minimum Income Condition concept and therefore facilitating the endeavor for efficient market representation of power generators.*

Relevant publications of the Author are [S2], [S3], [S4], [S5], [S7] and [S8].

2.2 Thesis 2

Looking at already operating PXs, two conspicuous general approaches can be found: these are usually referred to as the American (or US) and European market designs. The American approach is generally more centralized with a stronger regulator and integrated trading of ancillary services. One of the important differences is the handling of intertemporal dependencies such as limits on production ramping. American PXs incorporate these connections fairly simply by design [8], [9] but due to the prevalence of self-scheduling for generators, they are hardly assessed on European markets.

The latter practice has been put into question by recent trends. It is an unpleasant fact that European power plants with naturally convex ramping limits have to either rely on potentially unstable non-convex order types e.g. blocks and smart blocks [10] or apply sophisticated market price forecasting methods before bidding. At the same time, novel notions are appearing about integrated PX designs involving the trade of European systemic security reserves [11], [12] which would make the straightforward consideration of gradient limits essentially unavoidable.

The proposed all-European PX – probably as a reaction to these challenges – employs complex supply orders with Load Gradient Conditions (LGCs). Since their description in the official EUPHEMIA proposal [2] is rather short and ambiguous, their precise interpretation and implementation remain largely open questions. A working solution is presented in this section which utilizes useful concepts from the American PX model without violating the criteria of the European market clearing framework.

> **(Thesis 2)** *A new formulation has been found for complex orders with Load Gradient Conditions on the officially proposed all-European day-ahead power exchange which can be applied without the overall modification of the European market clearing framework. The acceptance rules of elementary bids – required by basic model structure – are designed to ensure the happiness of LGC bidders in the sense that they gain maximal surpluses considering given market clearing prices. This pricing scheme operates by introducing shadow prices for ramping restrictions, a concept based in the duality theory of optimization and widely used in American power exchange models. Since the resulting equations are linear, the computational efficiency of the European clearing framework is retained.*

Main results are summarized in publications [S1], [S4], [S6], [S7] and [S8].

2.3 Thesis 3

The order formulations described for MIC orders and LGC orders in Theses 1 and 2 cannot be used simultaneously for any complex order. The main obstacle is the deviation in bid acceptance rules. MIC orders need to use ordinary pricing to make the crucial income calculation procedure possible. On the other hand, LGC orders apply a kind of indirect pricing in which the acceptance or rejection of an elementary bid is not determined by its corresponding market price alone; they also depend on shadow prices of ramping limits. This latter approach is unavoidable if bidder happiness is required.

Complex orders with both MICs and LGCs attached can be called general complex orders (GCOs). Bidder happiness cannot be guaranteed for these orders because of the non-convex nature of MICs. In the case of rejections, bidders do not always gain maximal surpluses considering given prices (these cases are also known as paradoxical rejections). Nevertheless, this is the only context in which the spoiling of bidder happiness is admissible; accepted elementary bids of GCOs have to follow the pricing rules of LGC orders. The consequence is that in order to develop a working model for GCOs in the European clearing framework, a modified income calculation method has to be invented.

> (**Thesis 3**) *A new formulation has been found for complex orders with both Minimum Income Conditions and Load Gradient Conditions on the officially proposed all-European day-ahead power exchange. The new model originates from the separate models for Minimum Income Conditions and Load Gradient Conditions; the unification of these parts is performed in a way that retains their advantageous features such as the manageability using convex Mixed Integer Quadratic Programming solvers and the guarantee of bidder happiness concerning ramping limits. The key component of the new formulation is the modified calculation of complex order incomes: this task is carried out using auxiliary income components that consider the effects of ramping restrictions.*

Main results of this section are covered in the papers [S4] and [S9] of the Author.

2.4 Thesis 4

The efficient operation of electricity markets is achievable only if participants provide decent, undistorted data in submitted bids. Any deviation from this basic principle can be detrimental for the whole market. This claim is also relevant in the case of ramping capabilities because the entire clearing model of complex orders is invented to find the allocation that takes given gradient limits into account in the most appropriate way [13].

This property of truthtelling has origins in game theory, it is basically the same concept as the strategyproofness of general allocation mechanisms [14]. A mechanism can be called strategyproof if it provides no opportunities for participants to create decision strategies based on their expectation about the behavior of other actors. In a strategyproof electricity market auction, the best choice is always the straightforward, “honest” bidding: no advantages can be gained by distorting bid parameters regardless of the other orders on the market.

The modified income calculation makes it possible to analyze the basic market incentives of GCO bidders. The initial tests of the GCO model proposal reveal that the official GCO concept can lead to unexpected results in this regard.

> (**Thesis 4**) *It is shown that – under certain circumstances – complex orders with both Minimum Income Conditions and Load Gradient Conditions can create disincentives for bidders to specify their true ramping capabilities. The deliberate understatement of gradient limits can lead to larger allocations in trading periods when high market prices are expected with the final consequence of enhanced bidder surplus compared to the case of straightforwardly using the real parameters in offers. This phenomenon is potentially detrimental to the market and requires appropriate handling in the form of design changes or regulations.*

2.5 Thesis 5

Unified purchase prices were invented for the Italian PX in order to handle frequent congestions on inland transmission lines, hence the Italian abbreviation PUN (Prezzo Unico Nazionale) is widespread in Europe. The idea is that demand bidders should pay the same price in different price zones even in the presence of network bottlenecks; this operation is achieved by the definition of an independent specific price – the PUN – for purchasers which is calculated from corresponding zonal clearing prices.

The main problem is that the straightforward calculation of PUNs is not viable in a wider European setting because it introduces continuous non-convexities into the clearing model. With the corresponding equation included, the resulting mathematical program would belong to the category of non-convex mixed integer non-linear programs (MINLPs) which is one of the hardest problem class in the field of optimization [15]. A new model has to be found that can be solved by convex MIP algorithms.

> (**Thesis 5**) *A new formulation has been found for unified purchase prices on the officially proposed all-European day-ahead power exchange which can be used to incorporate them into the European market clearing framework without special algorithmic solution procedures. The explicit enforcements of income-expense balances in each trading hour are used to calculate unified purchase prices, an approach made possible by the integrated income determination for all bids and connection lines. The new model is compatible with the majority of officially supported order types and network conditions. It is the first formulation of unified purchase prices that can be handled by commercial generic Mixed Integer Programming solvers enhancing and extending the opportunities to implement and analyze this innovative concept.*

Most important scientific results of this section are included in publications [S2] and [S9].

3 Practical value of the theses

One of the most important advantages of integrated PX clearing models is that researchers do not have to directly handle the computational issues of experimental PX structures when complex orders are present. The use of professional convex Mixed Integer Quadratic Programming solvers becomes available and sufficient. Although the application of these software requires attention and experience, it is still substantially easier than the development or modification of problem-specific heuristics which are unavoidable without integrated models. This property of integrated model formulations is especially beneficial for large-scale industrial research projects and applications.

Most of the novel ideas presented in this dissertation arose during a research project of this nature. The project concerned the joint trading of electrical energy and system security reserves on the day-ahead PXs and has been completed in 2013-15. Its official title was "Electrical energy market modeling, simulation and experimental system development with research on co-optimization methods", and had the identifier GOP-1.1.1-11-2012-0583. The project was financed by the Hungarian government and the European Union.

The target was to create a European market design, a clearing algorithm and additional software tools for combined energy and reserve allocation. The main argument for the common market platform is that the energy supply and the reserves originate from the same capabilities of power plants. The consideration of mutual effects and dependencies increases market efficiency [16]. As a matter of fact, the separated day-ahead market of ancillary services in certain countries (e.g. Hungary) is much less liquid than the independent PX, a situation that leads to unstable and generally high reserve procurement prices. On the other hand, the incorporation of reserve products had to be achieved in a market environment that also satisfies the criteria of the all-European market coupling.

The latter condition infers that the market clearing model needed to include complex orders, therefore the efficient and exact implementation of these concepts were critical. Moreover, the proposals of this dissertation have also been useful as the basis of so-called combined energy-reserve offers [12]. Actually, combined bids are complex orders supplemented with upward and downward reserve price curves and regulation range limits. At the same time, they also keep the original complex order properties – e.g. Minimum Income Conditions and Load Gradient Conditions – described in EUPHEMIA specifications [2].

The three most important products developed in the described project:

- a market operator software aiming ideal resource allocation that also enhances system operation security;
- a market monitoring tool for the analysis of energy and reserve market processes;
- a trader training simulator that is capable of the construction and reconstruction of different trading scenarios for purposes of education and strategy-building.

Several practical results of the present dissertation – mostly in connection with the first three theses – have been integrated into the first listed product, the PX operator software. This software has been thoroughly tested and exploited for the analysis of several market scenarios [S8]. The direct application of commercial Mixed Integer Quadratic Programming solvers in AMPL have played a significant role in the success of the project.

Further developments of the specific objective concerning co-optimized European day-ahead PXs mainly depend on international support and cooperation.

4 Referred publications of the Author

[S1] Sleisz, Ádám. 2013. “Power Exchange Simulation as an Interactive Educational Tool.” In International Youth Conference on Energy. doi: 10.1109/IYCE.2013.6604129.

[S2] Sleisz, Ádám, Péter Sőrés and Dávid Raisz. 2014. “Algorithmic properties of the all-European day-ahead electricity market.” In 11th International Conference on the European Energy Market (EEM14). doi: 10.1109/EEM.2014.6861275.

[S3] Sleisz, Ádám, and Dávid Raisz. 2014. "Clearing algorithm for minimum income condition orders on European power exchanges." In Power and Electrical Engineering of Riga Technical University (RTUCON), 2014 55th International Scientific Conference on, 242-246. doi: 10.1109/RTUCON.2014.6998204.

[S4] Sleisz, Ádám, Dániel Divényi, Beáta Polgári, Péter Sőrés, and Dávid Raisz. 2015. “Challenges in the formulation of complex orders on European power exchanges.” In 12th International Conference on the European Energy Market (EEM). doi: 10.1109/EEM.2015.7216673.

[S5] Sleisz, Ádám, and Dávid Raisz. 2015. “Efficient Formulation of Minimum Income Condition Orders on the All-European Power Exchange.” *Periodica Polytechnica Electrical Engineering and Computer Science* 59 (3): 132-137. doi: 10.3311/PPee.8582.

[S6] Sleisz, Ádám, and Dávid Raisz. 2016. “Complex supply orders with ramping limitations and shadow pricing on the all-European day-ahead electricity market.” *International Journal of Electrical Power & Energy Systems* 83: 26-32. doi: 10.1016/j.ijepes.2016.03.061.

[S7] Sleisz, Ádám, and Dávid Raisz. 2016. „Clearing models of complex supply orders on European power exchanges.” Alkalmazott Matematikai Konferencia, Győr.

[S8] Polgári, Beáta, Ádám Sleisz, Péter Sőrés, Dániel Divényi, and Dávid Raisz. 2016. “Proposal of a New European Co-optimised Energy and Ancillary Service Market Design - Part II - Mathematical Model, Case Study and Prototype.” In 13th International Conference on the European Energy Market (EEM).

[S9] Sleisz, Ádám, and Dávid Raisz. 2017. “Integrated mathematical model for uniform purchase prices on multi-zonal power exchanges.” *Electric Power Systems Research* 147: 10-21. doi: 10.1016/j.epsr.2017.02.011

[S10] Sleisz, Ádám, and Dávid Raisz. „ New model and implementation of power plants’ general complex orders on European electricity markets.” *Journal of Electrical Engineering – Elektrotechnický časopis*, under review.

5 References

[1] European Parliament, Council of the European Union. 2009. „Directive 2009/72/EC.” *Official Journal of the European Union* 52: 55-93. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2009.211.01.0055.01.ENG&toc=OJ:L:2009:211:FULL.

[2] EPEX Spot, GME, Nord Pool, OMIE, OPCOM, OTE, TGE. 2016. *EUPHEMIA Public Description: PCR Market Coupling Algorithm*. https://www.nordpoolspot.com/globalassets/download-center/pcr/euphemia-public-documentation.pdf.

[3] Achterberg, Tobias. 2007. *Constraint Integer Programming.* PhD Dissertation. Technical University of Berlin, Berlin.

[4] Dey, Santanu S. 2010. *Cutting Planes in Mixed Integer Programming*. http://www2.isye.gatech.edu/~sdey30/IntroCuttingPlanes.pdf.

[5] Berthold, Timo. 2006. *Primal Heuristics for Mixed Integer Programs*. Diploma Thesis, Faculty of Mathematics, Technical University of Berlin, Berlin.

[6] APX, Belpex, EPEX Spot. 2011. *COSMOS Description: CWE Market Coupling Algorithm*. https://www.apxgroup.com/wp-content/uploads/COSMOS_public_description2.pdf.

[7] Meeus, Leonardo. 2006. *Power Exchange Auction Trading Platform Design*. PhD Thesis, Katholieke Universiteit, Leuven.

[8] Van Vyve, Mathieu. 2011. *Linear prices for non-convex electricity markets: models and algorithms.* http://uclouvain.be/cps/ucl/doc/core/documents/coredp2011_50web.pdf.

[9] Wu, Tong, Mark Rothleder, Ziad Alaywan, and Alex D. Papalexopoulos. 2004. “Pricing Energy and Ancillary Services in Integrated Market Systems by an Optimal Power Flow”, *IEEE Transactions on Power Systems* 19 (1): 339-347. doi: 10.1109/TPWRS.2003.820701.

[10] EPEX Spot. 2014. *EPEX Spot: Introduction of Smart block bids – Linked block orders and exclusive block orders*. https://www.epexspot.com/document/25495/Smart%20blocks%20-%20presentation.

[11] Chatzigiannis, Dimitris I., Pandelis N. Biskas, and Grigoris A. Dourbois. 2016. “European-Type Electricity Market Clearing Model Incorporating PUN Orders.” *IEEE Transactions on Power Systems*. doi: 10.1109/TPWRS.2016.2542823.

[12] Polgári, Beáta, Péter Sőrés, Dániel Divényi, Ádám Sleisz, Dávid Raisz. 2015. "New Offer Structure for a Co-optimized Day-ahead Electricity Market." 12th International Conference on the European Energy Market (EEM15). doi: 10.1109/EEM.2015.7216668.

[13] Oren, Shmuel S., Andrew M. Ross. 2005. “Can we prevent the gaming of ramp constraints?,” *Decision Support Systems* 40 (3–4): 461-471. doi: 10.1016/j.dss.2004.05.008.

[14] Muller, Eitan, Mark Sutterthwaite. 1983. *Strategy-Proofness: The Existence Of Dominant Strategy Mechanisms*. https://ideas.repec.org/p/nwu/cmsems/568.html.

[15] Burer, S., Letchford, A. N. 2012. "Non-convex mixed-integer nonlinear programming: A survey." *Surveys in Operations Research and Management Science* 17 (2): 97-106. doi: 10.1016/j.sorms.2012.08.001. FICO. 2009. *Xpress-Mosel User Guide: Release 3.00*. http://www.fico.com/en/wp-content/secure_upload/Xpress-Mosel-User-Guide.pdf.

[16] Sőrés, Péter M., Dániel Divényi, Beáta Polgári, Dávid Raisz, Ádám Sleisz. 2015. "Day-ahead Market Structures for Co-optimized Energy and Reserve Allocation." 12th International Conference on the European Energy Market (EEM15). doi: 10.1109/EEM.2015.7216667.