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Heuristic solutions to the long-term unit commitment problem with cogeneration plants

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ABSTRACT

We consider a long-term version of the unit commitment problem that spans over one year divided into hourly time intervals. It includes constraints on electricity and heating production as well as on biomass consumption. The problem is of interest for scenario analysis in long-term strategic planning. We model the problem as a large mixed integer programming problem. Two solutions to this problem are of interest but computationally intractable: the optimal solution and the solution derived by market simulation. To achieve good and fast approximations to these two solutions, we design heuristic algorithms, including mixed integer programming heuristics, construction heuristics and local search procedures. Two setups are the best: a relax and fix mixed integer programming approach with an objective function reformulation and a combination of a dispatching heuristic with stochastic local search. The work is developed in the context of the Danish electricity market and the computational analysis is carried out on real-life data.

1. Introduction

In the Danish electricity market there are multiple generating companies that produce electricity from fuel combustion in thermal power plants or from wind mills, and only one transmission company that controls the transmission grid. The electricity produced is set for sale by the generating companies on an electricity exchange and it is bought by trading companies, who then sell it to the end users.

Cogeneration power plants generate beside electricity also heating. Denmark is divided into a number of *heating regions* and cogeneration plants can only supply heating to the region where they are located while they can transfer electricity to other regions and to neighboring countries. On the other hand, heat can be stored in accumulators while electricity cannot.

The electricity exchange for the Nordic region is the NordPool exchange.[1] Here the price of electricity is determined by *standard market equilibrium* and all the electricity is sold at this equilibrium price. In efficient markets companies use marginal production costs as their offering price for electricity. Companies with a dominating position in such a market could force the price up by offering electricity at higher prices. However, a number of past legal disputes in Denmark have made it clear that such strategic behavior is illegal, and that in spite of their dominating position companies should offer electricity at a price close to the marginal production costs. Wind energy that has no variable production costs is offered at the market at cost zero.

The process of offering electricity and bidding for it at the NordPool exchange is done every day before noon for the 24 h of the following day. After the process has finished the generating companies receive a load profile specifying the amount of electricity they have sold in each of the 24 h. It is thus possible for the generating companies to optimize production for the 12 h left in the current day and for the 24 h of the next day. Updates on wind forecast arrive typically every hour and this offers the possibility for reoptimizing the production plan on hourly basis. This possibility is only available to generating companies that have in their portfolio both windmills and power plants with flexible production.

Turning a power plant on and off causes an extra cost. In many cases, when the demand for electricity drops, stopping power plants can be avoided by reducing production over a set of plants. In some situations the demand drops to a level lower than the sum of the running plants minimum production level. To avoid start-up costs here, it is possible to keep the power plants running and produce at their minimum capacity, thus paying only for the fuel consumption. Since it is not possible to accumulate electricity, the excess of electricity must then be sold to the neighboring countries, possibly at a price lower than the production costs. The trade-off between paying for expensive start-ups and producing extra power is central in optimizing the production.

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[1] NordPool website: http://www.nordpool.com. See also http://www.nordpoolspot.com.

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Finding a good production plan for one single generation company after the amount of electricity sold becomes known corresponds to a variant of the *unit commitment problem*. This problem is well studied in the literature, see e.g. [16,21]. A solution comprises a *unit commitment schedule* that determines which plants are running in every hour; and an *economic dispatch plan* that determines the production level of these plants. The goal is minimizing production costs in a time horizon of 24 h or a few days divided into time intervals of length from 1 h to 5 min, while, at the same time, satisfying constraints on electricity demand, heating demand, heat accumulators, a spinning reserve and ramping limits. We refer to this problem as the *short-term unit commitment* (ST-UC) problem.

In this article, we look instead at a tool to simulate scenarios over a one year time horizon. Such a tool is of interest for generating companies and for governments who want to foresee long-term effects of investments, competitor behavior, policy changes and other long-term decisions. From the perspective of a single generation company this tool may provide information on the effect of internal strategic decisions or external changes. Example of the latter are: changes in connection capacity to neighboring countries, changes in electricity prices in those countries and changes of competitors' power plants in the region. We look therefore at an extended formulation of the unit commitment problem, based on a complete model that includes not just one single generation company but all competing generation companies acting in the market as well as connections to the neighboring countries. The electricity demand considered in this formulation is the aggregate demand of the country and the one-year time horizon is divided into time intervals of 1 h.

In addition, we include a biomass constraint that takes into account regulations to use (at least) a certain amount of biomass per year. The regulation is needed at time of writing because biomass is more expensive than fossil fuels like coal or oil and hence companies would tend not to use it. In the future, if the prices of CO_2-emissions were to increase, the constraint might become unnecessary.

We call this extended formulation *long-term unit commitment* (LT-UC) problem. Over long time periods, wind production, foreign electricity prices and demand are highly uncertain, hence a long-term plan is not to be put into practice without changes in the daily operation. As a tool for scenario analysis instead, one wishes to try several different alternatives. Hence, due to this form of interaction a solution to the LT-UC problem has to be found relatively quickly. In this article, we aim at solvers whose total running time is of the order of a few minutes.

Both the ST-UC and LT-UC problems can be formulated as mixed integer programming (MIP) problems. With regard to the LT-UC there are two solutions of interest. The first is the off-line optimal solution, which is of natural and comparative interest. The second is the on-line solution given by the market mechanism described above, that is, every hour a new ST-UC problem is solved with time horizon of 24–48 h and time intervals of down to 5 min. The solutions are then combined to give a solution for the whole year. We will call this latter solution a *market simulation* and restrict it to account for 24-h problems with time intervals of 1 h. The market simulation can yield solutions different from the off-line optimal solutions because it looks only at a restricted time window in comparison with the all-year knowledge of wind and demand levels of the off-line optimal solution. However, a solution close to the market simulation is of interest because it may describe more closely what would happen in practice. While a comparison with the off-line optimal solution may be used to gain insight on how efficient the current market is. Both market simulation and off-line optimal solution are however intractable by MIP in computational terms if, like in the Danish context, 20 plants are to be scheduled over a one year time horizon for time intervals of 1 h. In these cases the resulting MIPs have far too many variables and constraints. In our experience even state-of-the-art solvers like CPLEX 12.2 are unable to solve the complete model given in Section 2.2 to a satisfactory quality within 24 h of computation time.

Most of the published research on unit commitment is on the ST-UC problem without heating constraints. A large number of methods have been studied on this problem including, among others, branch and bound, Lagrangian relaxation, priority listing, genetic algorithms, simulated annealing and tabu search [16,21]. Lagrangian relaxation is perhaps the most popular approach, and the first attempts, are to our knowledge, those by Muckstadt and Koenig [15], Merlin and Sandrin [14] and Bard [2]. Other applications include the works by Borghetti et al. [4] and Frangioni et al. [9]. The popularity of Lagrangian relaxation is partly due to the fact that it makes it possible to handle complex constraints on the local units (for example, time dependent starting costs and ramping constraints). This is because the binding constraints, most often the electricity demand, are relaxed and the problem decomposed into a subproblem for each unit. These relaxed subproblems can often be solved efficiently to optimality, see Frangioni and Gentile [8]. Lagrangian relaxation has been compared with a tabu search approach in [3], where the authors conclude that the performance of the two methods is similar.

Dotzauer et al. [6] consider the ST-UC for cogeneration plants with the possibility to store heat in accumulators. They consider a small instance with a few plants, and optimize the heating production and storage by a Lagrangian relaxation approach, relaxing the heating demand and accumulator balance constraint. They assume the units operate in a competitive energy market so electricity can be sold at a known and fixed market price. This means that they do not include electricity demand constraints in the model and only decide whether to produce energy or not based on the fuel costs and the market price of electricity. This differs from our case where we want to include constraints on both electricity and heating demand.

Hakonen et al. [13,19,20] consider one year linear programming models for cogeneration systems. They develop the (extended) power simplex algorithm—a problem specific version of the simplex algorithm. However, these models differ from the LT-UC problem in that they do not include start–stop costs and the possibility to store heat. Thus, the yearly problem decomposes into hourly subproblems. The extended power simplex algorithm could then be used in the work presented here only for optimizing the economic dispatch plan (ignoring heating storage).

Perhaps, the closest form of long-term unit commitment problem in the literature is a ST-UC with a time horizon of a few weeks. Voorspools and D'haeseleer [23] consider the one week horizon and they compare a unit decommitment method with a priority listing method, concluding that the performance is almost the same, but the priority listing is around 5–10 times faster. Thorin et al. [22] consider problems of 5 and 6 weeks with heating constraints. The problems are formulated as MIP problems and broken into overlapping subproblems which are then handled by a MIP-solver.

Our contribution in this article is the study of heuristic approaches for the LT-UC problem over the time horizon of one year. The heuristic algorithms designed are obtained by assembling different modules that use appropriate methods to address different aspects of the problem. We distinguish construction heuristics and improvement methods. One is a construction heuristic based on mixed integer programming to decide the on/off status of the plants (unit commitment schedule) followed by a linear programming post-processing to determine the production levels (economic dispatch). The other is a simple