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Combined heat and power production planning under liberalized market conditions

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A B S T R A C T

This paper presents a methodology for optimization of technological operations in a CHP plant and for simultaneous planning of electricity trading with profit maximization being the objective. A general modelling framework is developed, which is aimed at rapid CHP plant models prototyping using an object-oriented modelling language. The framework consists of two main parts – first-principle models of technological components and a model of trading with standardized power products on power markets. The complexity of models is chosen considering their further implementation within a mixed-integer linear optimization problem. The choice of linear and piece-wise linear problem formulation results from the need of its applicability for practical problem instances, while non-linear descriptions usually involve unacceptable computational times. Using the proposed methodology and general-purpose solver Gurobi, optimal solution for short-term problems (24–48 h) are found within few minutes. In the case of medium- and long-term problems (weeks to months), near optimal solutions (with an error usually under 0.5% and 1.0% respectively) are found within 2 h.

1. Introduction

The main task of district heating plants with combined heat and power (CHP) production is to supply a district with heat. Additionally, these plants often supply industrial processes with hot water and/or steam and trade the cogenerated electricity on power markets. CHP plants are therefore very complex systems and planning of their technological operations represents a very complicated problem. The recent liberalization of energy markets brought additional degrees of freedom (market opportunities) which made the problem even more difficult. Before the liberalization CHP plants usually generated as much electricity as possible considering the heat demand which the plant is obliged to satisfy. However, after the liberalization, electricity is typically traded in the form of standardized power products on power markets. The delivery pattern of a power product is strictly specified and any deviation is penalized. Therefore, apart from the plan of technological operations also a combination of different power products to be traded is sought. In this paper this task is formulated as an optimization problem and an approach for its solving is presented.

The goal is to provide a methodology general enough to be usable for any district heating plant. The methodology should handle real-world instances of the problem and solve them in reasonable computational times.

1.1. Literature survey

In order to formulate the optimization problem a model that describes the system is needed. In literature two basic approaches for CHP plant modelling were used

- black-box approaches using data interpolation [1] or defining operating regions of whole CHP plants [2] or of individual components [3]
- and first-principles approaches employing balance equations [4–9].

The main advantage of the first-principles approach is its generalization capability. It can therefore be used even when historical data are not available or incomplete and it can offer solutions that were not considered before. On the other hand a black-box model can credibly propose only solutions that are included in the historical data it was identified from. If the historical data is incomplete simulations of a first-principle model may be performed to obtain the missing data needed for regression analysis as was shown in [10].

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In literature the first-principles modelling of CHP plants was usually addressed in a different scope than district heating - usually process integration problems of utility systems [6,9] with different emphases on model complexity. As only single-period optimization or multi-period optimization without time-coupling constraints is considered, more complicated (non-linear) models may be used while computational times remain acceptable.

First-principle models of small industrial cogeneration plants for operations scheduling were developed in [3–5], where non-linear (higher-order polynomial) descriptions of condensing turbines were used. In these cases, no complicating constraints on components operation, such as ramping limits or minimum up add down times, were modelled. These papers also address electricity trading. The produced electricity is sold regardless on its volumes (within a bilateral agreement) and no special delivery pattern is required. Yet, many CHP plants are either forced to participate on the trading with power products (have no favorable bilateral agreements) or they recognize a good market opportunity in it. Electricity trading of CHP plants in the form of standardized power products has not yet been dealt with in known literature before.

There are several publications emphasizing the generality of modelling frameworks in the scope of CHP plants. In Ref. [10] a general non-linear model of a CHP plant is developed. This model is then used for optimization problem formulation dealing with biomass integration. Also in [11] a general dynamic model of a combined-cycle plant is developed with special emphasis on object-oriented programming. The modelling framework is developed for the purpose of its implementation into a software by means of Modelica language.

In recent literature, the optimization problems of CHP operations scheduling were solved using metaheuristics [5] or by general-purpose solvers (specialized software packages) for mixed-integer linear [2,3] or non-linear problems [9,10]. While a specific problem formulation is needed when a general-purpose solver is used, metaheuristics require no special description. Nevertheless, the great advantage of solvers for mixed-integer linear programming (MILP) problems and also for some special classes of non-linear problems is the provision of the optimality certificate. Besides, an estimation of proximity to the optimal solution is provided during the solution process. Metaheuristics are, on the other hand, purely non-deterministic.

Mixed-integer non-linear programming (MINLP) problem is possibly an ideal representation for our optimization problem with respect to model accuracy as was shown in [9] where a non-linear process integration problem with several hundreds of variables is tackled. A non-linear biomass integration problem of similar size is also solved in [10]. In Ref. [9] the MINLP problem was found too computational demanding for a general-purpose solver and the computational complexity is tackled by the method called Successive MILP. MILP computations are followed by non-linear simulations updating operation point for linearization. In Ref. [10] the problem was solved by a general-purpose solver for non-linear problems. Relatively small non-linear problem instances can therefore be handled, either by state-of-the-art general-purpose non-linear solvers or by solvers developed for particular problem instances. Unfortunately, at present no solver for MINLP problems can handle the problems as large as this paper deals with (up to hundreds of thousands variables).

To summarize the results of the state-of-the-art analysis:

- contributions dealing with power products trading are missing;
- the proposed models are either black-boxes or defined for different scopes with different emphases on model accuracy;
- generality of the modelling approaches is insufficient which limits its applicability in practice;
- constraints such as ramping limits or minimum up and down times are often not considered.

1.2. Proposed methodology

The goal is to develop a methodology for CHP operations and trade planning which would be readily applicable to the majority of district heating plants with CHP production. The generality of modelling framework is therefore required. Also, the framework is aimed at an object-oriented modelling language.

Operators of district heating plants require the plan of operations to be provided in terms of mass flows through thermodynamic components, fuel and allowances consumption and power outputs of turbines. The plan of trade then should consist of instructions which products to trade in what volumes. The decisions are based on heat demand predictions, costs of fuel and allowances and (expected) electricity prices. The important features of the presented methodology are:

- hour granularity of proposed plans,
- planning horizons from days (short-term operations plans) to months (futures trading),
- user-definable power products,
- reasonable computational times (up to 10 min and 2 h for short- and long-term problems),
- inclusion of ramping limits, minimum up and down times and start-up costs.

2. Modelling framework

The bottom-up and first-principle approach has been chosen for the modelling of CHP plants. As mass flow and energy transfer rates are the values of interest (considering the required output of the optimization problem), mass rate and energy rate balance equations represent a suitable way of modelling the thermodynamic cycles of CHP plants. This way the system can also be broken up into a set of connected components which conforms the modelling approach of an object-oriented modelling language.

With respect to the state-of-the-art analysis the MILP approach was chosen for the formulation of the optimization problem. The main drawback of the MILP problem representation, the need for linear description, is dealt with piece-wise linear (PWL) approximations of non-linear functions.

The model is defined in discrete time in time samples t with sampling period of 1 h. This sampling period has been chosen according to the needs of customers as the electricity is traded with the granularity of 1 h. Hence in order to work with power product definitions properly, the sampling period cannot be longer than 1 h. Also, for the purpose of planning the granularity of 1 h is sufficient as the faster dynamics is not of interest in the view of operations plans.

In the following paragraphs the modelling framework is presented on the example of a medium-size district heating plant in Fig. 1. The topology is taken from a real plant in the Czech Republic with rated power outputs of 50MW in heat and 40MW in electricity. The plant also provides steam of defined parameters for an industrial site.

2.1. Generalized component of the thermodynamic cycle

In accordance to the need of generality of the modelling framework a generalized component is defined. Its definition conforms the utilization of the component within MILP