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Genetic optimization of multi-plant heat production in district heating networks

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HIGHLIGHTS

- Utilization of smart meter information for optimizing district heating (DH).
- Simultaneous optimization of DH production at multiple plants.
- Genetic algorithm operating on top of a DH system simulation model.
- Extensive sensitivity analysis of supply temperatures and load allocation.
- Savings due to lower production and distribution costs of DH.

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ABSTRACT

Smart metering is providing spatially and temporally much more accurate and detailed customer level information about district heating (DH) consumption than before. Currently this information is mainly used for billing only, but it could be used to operate the system more efficiently. In this study we develop a new method for optimizing the heat production simultaneously at multiple heat plants at different locations of a DH network in order to minimize the combined production and distribution costs. Optimization determines the optimal supply temperatures at different heat plants and optimal load allocation between the plants. The method can be used to optimize the current heat production based on real-time customer measurements. The method can also be used for production planning based on more accurate and detailed customer level demand forecasts. Optimization is based on a static DH system model that can estimate the state of the entire DH network based on real-time measurements or demand forecasts. Because the objective function is a non-convex and non-smooth function of the decision variables, we use the genetic algorithm (GA) to solve the problem. The method can be applied to arbitrary DH networks with multiple heat plants. Optimization can result in savings in fuel and pumping costs. We illustrate the method with a sample district heating network with two parallel heat plants and real-life DH network segments. We also show extensive sensitivity analysis results for the two-plant case.

1. Introduction

District heating (DH) has been widely utilized in many European Countries since the beginning of the 20th century. In Finland, nearly half of the heating market was covered by DH in 2011 [1]. DH technology has many advantages such as high energy efficiency of heat production, low level of emissions [2], possibility to use various fuels, utilization of heat storages and customer-friendliness. DH can have a renewable energy supply stock and it works well also with other renewable energy technologies [2,3], particularly if provided with heat storage [4]. DH also allows regulating emissions in centralized plants. The high energy efficiency of DH systems in comparison to other heating options has been shown in various studies. For example, the general advantages of DH (and cooling) systems were discussed in [5,6]. Surplus heat from industrial processes can also be utilized in DH systems; then DH enables further enhancement of efficient resource use. For the customer, DH is an economical and user-friendly heating solution. However, large investment costs, as well as heat losses during distribution of the heat are challenging DH companies to make wise decision about network design and operation in order to achieve a good performance with high efficiency.

DH can connect multiple heat demands with various energy sources [7]. Combined heat and power (CHP) production is

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Nomenclature

Abbreviations
CHP combined heat and power
COH cost of heat (€ per MW h)
DH district heating

Index sets
N set of nodes in the DH network $N = N^{plant} \cup N^{cust} \cup N^{inter}$
N^{cust} set of customer nodes
N^{branch} set of nodes where three or more branches meet
N^{inter} set of intermediate nodes
N^{plant} set of plant nodes
R set of DH pipes $\langle i,j \rangle$ connecting nodes

Variables
d_i mass flow rate (demand) at customer node (+), plant node (−) or intermediate node (0), (kg/s) ($i \in N$)
$\dot{m}_{i,j}$ mass flow rate in supply and return pipes $\langle i,j \rangle$ (kg/s) ($\langle i,j \rangle \in R$)
T_i^s supply water temperature at node i (°C)
T_i^r return water temperature at node i (°C)
$T_{(i)j}^s$ temperature of incoming supply water from node i to branching node j (°C) $\left(j \in N^{branch}\right)$
$T_{(j)i}^r$ temperature of incoming return water from node j to branching node i (°C) $\left(i \in N^{branch}\right)$
$\dot{Q}_i$ heat production rate at the plant node i (W) $\left(i \in N^{plant}\right)$

Parameters
Φ overall heat loss (W)
ρ density of water (kg/m^3)
C_e electricity price for pumping the water (€/kW h)
C_i variable costs of operation, maintenance and administration (€/MW h) $\left(i \in N^{plant}\right)$
c specific heat capacity of water (J/(kg °C))
$\dot{D}_i$ heat demand rate at the customer node i (W) ($i \in N^{cust}$)
$d_{i,j}^I$ inner diameter of pipe (m)
$d_{i,j}^o$ outer diameter of pipe (m)
$K_{i,j}$ heat transmission coefficient for the pipes between nodes i and j, in terms of the outer pipe surface (W/m^2 °C)
$l_{i,j}$ the length of pipe $\langle i,j \rangle$ (m)
T^g ground temperature (°C)

currently the main technology for producing heat in many DH systems. In Finland, CHP produces approximately 74% of DH [8]. However, the CHP plants are normally built to cover only the basic heat demand while peak demand is satisfied with heat-only boilers (HOBs) that have cheaper investment costs but are more expensive to operate. In general, a DH system can have multiple CHP plants and HOBs that can be launched to assist heat production. In production planning, one task is to determine which plants should operate (unit commitment of plants) in any given situation, and how the heat load should be distributed among them.

Earlier research has investigated the configuration of the peak boiler, i.e. evaluated how the capacity and location of the peak boiler should be determined [9]. In [10] the operational planning problem of district heating and cooling units at a single location was formulated as a mixed 0–1 linear programming problem that was approximately solved using a genetic algorithm (GA). Li and Svendsen [11] optimized the configuration of a DH network connecting a single heat plant to the customers. The review [12] summarized three main families of heat transfer problems using GA: thermal systems design problems; inverse heat transfer problems; and development of heat transfer correlations. Operation of DH systems with multiple plants at different locations is common knowledge for major DH and consulting companies. Instead of optimizing the operation of multiple plants, DH companies typically apply heuristic rules when determining the load allocation between plants. No academic research has addressed the operational optimization of DH production with multiple plants at different locations.

The novelty of this study is that we develop a GA based method for the operational combined production and distribution problem of DH with multiple heat plants (CHP or HOB) at different locations of the network. We assume a fixed configuration and pre-determined unit commitment. The operating costs consist of variable production costs at the heat plants and distribution costs in the DH network. The production costs consist mainly of fuels costs. For CHP plants there are different conventions for how to allocate the production costs on power and heat. Most commonly the production costs are allocated in a fixed ratio according to energy or exergy production. In the presence of a power market, heat and power have an asymmetrical role, because produced power can be sold freely on the market at market price, but heat must be produced to meet the demand as the heat business is a natural monopoly. In [13], the marginal production costs for power and heat commodities were computed using parametric analysis. In any case, the production cost of heat will depend on the amount of heat produced. The distribution costs consist mainly of electricity costs for pumping [14].

Cost-efficient operation of multiple heat plants is highly desirable for DH companies to remain competitive against other forms of heating. Earlier, detailed customer measurements were not available. For this reason, the heat companies did not know in real-time in what state the network was operating in. Currently most DH companies still determine the supply temperature based on present or forecasted outdoor temperature. Furthermore, the supply temperature is set to a conservatively high value to guarantee that all customers receive enough heat at a high enough temperature. Quality errors in substations and customer heating systems require providing heat at an overly high supply temperature [15,16]. Now, smart metering is providing real-time customer measurements, which facilitates much more accurate operation of a DH system. Therefore, optimization may lead to savings in fuel consumption and also smaller emissions in case of fossil fuels [17]. Even when the fuel is renewable biomass (such as wood chips or pellets), it is important to use the fuel efficiently. Overall, it is very important for a heating system to make efficient use of energy and to increase the share of renewable energy resources so that the fossil fuel consumption is reduced. Saving energy cost and reducing environmental pollution while meeting the customers' heat demand have become the primary focus for DH systems [18].

In this paper, an optimization model for heat production at multiple heat plants is developed on top of a static network calculation model that is based on our earlier research [19]. The network model can estimate the state of the entire DH network based on customer measurements or demand forecasts for customers. We have also earlier developed a demand forecasting model based on customer measurements [18], and that model can be applied