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Innovative Applications of O.R.

An optimization approach for district heating strategic network design

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ABSTRACT

District heating systems provide the heat generated in a centralized location to a set of users for their residential and commercial heating requirements. Heat distribution is generally obtained by using hot water or steam flowing through a closed network of insulated pipes and heat exchange stations at the users' locations. The use of optimization techniques for the strategic design of such networks is strongly motivated by the high cost of the required infrastructures but is particularly challenging because of the technical characteristics and the size of the real world applications.

We present a mathematical model developed to support district heating system planning. The objective is the selection of an optimal set of new users to be connected to an existing thermal network, maximizing revenues and minimizing infrastructure and operational costs. The model considers steady state conditions of the hydraulic system and takes into account the main technical requirements of the real world application. Results on real and randomly generated benchmark networks are discussed.

1. Introduction

A good energy policy should be focused on two main aspects: the reduction of energy consumption and a better use of the available sources. From this point of view, District Heating (DH) is an important resource to reach environmental sustainability and energy efficiency of modern cities. Broadly speaking, DH concerns the centralized production of thermal and possibly electrical energy and its distribution to a network of users, thus obtaining much higher efficiency in the production and maintenance costs with respect to the individual production by the end-users (see, e.g., Gustavsson, 1994; Nitsch, Krewitt, & Langniss, 2004, chap. 4) . During the last decades DH has reached a considerable diffusion not only in northern Europe, but also in central and southern European countries, North America and Japan. Just to give an example of the steep trend line of DH systems implementation, in Italy from 2000 to 2010 the number of towns having DH networks increased from 27 to 104, the kilometers of pipe raised from 1000 to about 3000 and the thermal and electric capacity produced more than doubled, reaching 7700 gigawatt hours (see EuroHeat & Power, 2013). This also correspond to a yearly saving of 1.3 megatonnes of CO_2. A similar growing trend can be found in other European nations (see Table 1) and also in other countries such as China – with 147,000 kilometers of pipes and 338 gigawatt hours – and Canada, where Dalkia serves 19 towns with a total DH extension of about 30 megameters. For more information about the DH infrastructures diffusion the reader is referred to the survey (EuroHeat & Power, 2013), performed in 2013 by EuroHeat & Power, the European association of district heating and cooling.

Starting from early infrastructures fed by traditional boilers, the DH networks saw a progressive increase in the complexity of the energy production system, which today are mainly based on modern Combined Heat and Power (CHP) systems with co-generation engines, and in many cases integrate renewable energy sources such as Waste-to-Energy, Solar, Geothermal and Biofuel engines.

The main aim of this paper is to show how mathematical optimization techniques developed within operations research may offer appropriate methods to support planning and management activities in the DH field. In particular, we focus our research on finding a viable quantitative methodology to support strategic decisions and commercial policies related to the connection of new users to an existing DH network. The resulting optimization problem is modeled through the application of graph theory and integer linear programming (ILP) paradigms. To better explain the problem we study, let us consider Fig. 1 which depicts a simple DH network whose nodes and links are associated with the following elements: one plant (represented by node 1), a set of existing users already connected to the network (i.e., nodes 4, 7 and 13), a set of

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Table 1
Development of DH infrastructures in some European countries (source EuroHeat & Power, 2013 survey; EuroHeat & Power, 2013).

Country	Served citizens (percent)	Pipelines (kilometers)	Heated surface (square megameters)	Heating capacity (megawatt hours)	Cooling capacity (megawatt hours)
Austria	21	4376	57	9500	35
Denmark	61	30,288	n.a.		
France	7	3644	n.a.	16,293	668
Germany	12	20,151	438	49,931	161
Italy	5	2951	96	2556	
Poland	5	19,286	472	59,790	
Sweden	42	21,100	678	15,000	650

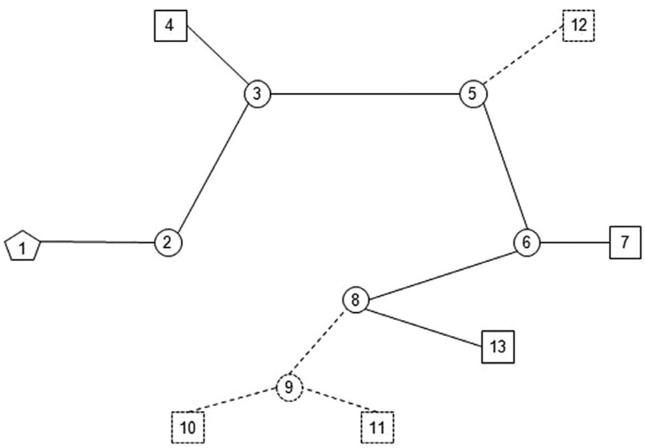

Fig. 1. An example of a generic district heating network. The pentagon represent the plant, squares represent existing or potential users, circles are tees and other junctions in the pipe networks, solid lines are existing pipes and hashed lines are potential ones.

potential users that can be connected to the network in the future (i.e., nodes 10, 11 and 12), a set of pipes which connect the existing users (i.e., the links in solid lines) and a set of potential pipes (i.e., the links in dashed lines) which might be lied down when potential users are connected to the network. Our strategic network design problem aims at deciding which potential users can be connected to the network in order to maximize the overall profit for the energy provider, while respecting the physics and hydraulic operational conditions of the system. As shown in the remainder of the paper the optimal solution of such a problem is then obtained by constructing a graph representation of the DH network and considering an ILP model which is then solved through a commercial solver.

The optimization of DH networks has received relatively little attention in the literature. A first type of modeling approaches aims at representing in detail the network physics through sets of non-linear equations derived from the thermo and fluid dynamic theories. In this way one generally obtains a very good precision of the representation of fluid distribution and thermal gradients along the different network components. However, the algorithmic difficulty of the solution of the required non-linear relations makes such approaches not adequate to model large networks, as those found in real-world applications where hundreds of users are served by the DH system. In this case, aggregation techniques of the network elements are often used to reduce the size enough to permit the numerical solution of the model at the expense of the accuracy of the network representation. Examples of non-linear models for DH network design are presented by Bøhm, Pálsson, Larsen, and Ravn (2008), and Park, Kim, and Kim (2000) while network aggregation techniques are discussed in Larsen, Bøhm, and Wigbels (2004), Larsen, Palsson, Bøhm, and Ravn (2002), Loewen, Wigbels, Althaus, Augusiak, and Renski (2001a, 2001b), Zhao (1995) and Zhao and Holst (1998). An alternative modeling of the DH networks is based on their empirical simulation starting from observation of temperature and pressure distributions of the real system (see, e.g., Benonysson, Bøhm, & Ravn, 1995; Pálsson, 1993). Such approaches require long observations of the system to get sufficient accuracy and are not suited to study different system configurations with respect to the observed ones. Network simulation was also used by Wernstedt, Davidsson, and Johansson (2003) to study the performance of different real-time control strategies for DH network management. An integer programming model for a different network design problem was defined by Aringhieri and Malucelli (2003). They considered the optimal selection of the type of heat exchangers to be installed at the users in order to optimize the return temperature at the plant and achieve good system efficiency at a reasonable cost. Finally, the design of the energy production plant integrating cogeneration engines and renewable energy was recently examined by Reini, Buoro, Covassin, De Nardi, and Pinamonti (2011), who developed integer programming models capable of solving small-scale examples.

Our research was motivated by the *Innovami* project financed within the regional program *PRRIITT*, activated by Emilia-Romagna regional authority to promote and support industrial research, innovation and technology transfer. During the project a prototype of the model presented hereafter was developed in collaboration with a local utility company and tested on a small-scale realistic network. Following the positive evaluation by practitioners the model was further extended in partnership with OPTIT, a spinoff company of the University of Bologna, making it possible to solve large-scale networks. The model represents the main hydraulic constraints of the real-world networks and constitutes an effective compromise between the accuracy of representation of physical behavior and the capability of handling realistic instances of the problem.

The paper is organized as follows. In Section 2 we present the main technical characteristic of a DH network and we introduce the required notation as well as the graph representation of the network. The mathematical model developed for supporting DH system optimal planning is described in Section 3. The computational testing of the model large-scale randomly generated networks and on a real-world one is presented in Section 4, while Section 5 draws some conclusions and illustrates possible future developments of the model.

2. Introduction to district heating network design

A DH network is made up by one or more energy production plants and a network of insulated pipes through which a hot fluid (usually hot water or steam) can flow from the plants to the users connected to the network. When the hot fluid reaches a user its heat is transferred to a heat exchanger. The fluid cools down and can flow back to the production plant, which provides warming up