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Innovative Applications of O.R.

Optimization models for a single-plant District Cooling System

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ABSTRACT

A District Cooling System (DCS) is an interconnected system encompassing a centralized chiller plant, a Thermal Energy Storage (TES) unit, a piping network, and clusters of consumers' buildings. The main function of a DCS is to produce and deliver chilled water to satisfy the cooling demand of a scattered set of buildings. DCSs are recognized to be highly energy efficient, and therefore constitute an environment-friendly alternative to the traditional power-driven air conditioning systems being operated at individual buildings. In this paper, we investigate the optimal design and operation of a DCS so that the total investment and operational costs are minimized. This involves optimizing decisions related to chiller plant capacity, storage tank capacity, piping network size and layout, and quantities to be produced and stored during every period of time. To this end, mixed-integer programming (MIP) models, that explicitly capture the structural aspects as well as both pressure- and temperature-related requirements, are developed and tested. The results of computational experiments that demonstrate the practical effectiveness of the proposed models are also presented.

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1. Introduction

Driven by the anticipated increase in energy demand and knitted together with a rapid rise in CO_2 emission levels, the notion of sustainable energy systems is gaining an ever-growing attention worldwide. One example of such systems is the so-called *District Cooling System (DCS)*. The main function of a DCS is to mass-produce cooling requirements for a group of buildings while ensuring tailored provision to each of them, depending on their needs. Hence, DCS appears as an alternative to the power-driven air conditioning systems being operated at individual buildings. Worldwide, the current status quo of energy usage shows that at least 10 percent of electricity is used for cooling purposes (DHC/+ Technology Platform, 2009). This percentage is even much higher in some hot climatic countries such as the Gulf Cooperation Council (GCC) countries, where air conditioning accounts for 50 percent of its annual electricity consumption (Booz & Company, 2012). For that reason, DCSs are recently gaining a remarkable market position across the globe as they can reduce electricity consumption by 40 percent–50 percent comparing to conventional air conditioning systems (Arab Construction World, 2012).

Currently, DCSs are adopted in the United States, Japan, Korea and many Western and Eastern European countries such as Austria, Finland, France, Germany, Italy, Norway, Slovenia, and Sweden (Euro Heat & Power, 2013). Generally, the market of DCS has not matured enough as it emerged quite recently; yet, its adoption trend is on the rise. For instance, a 10-fold growth in its installed capacity was observed in Europe during the last decade (DHC/+ Technology Platform, 2009). Nonetheless, DCSs are recently gaining ground in the Middle East, particularly in the GCC countries due to their desert climate. For example, it was observed that 14 percent of GCC cooling demand was satisfied by means of DCSs in 2010 (Arab Construction World, 2012).

Structurally, a DCS is an interconnected system encompassing a centralized chiller plant, a main distribution network and clusters of consumers' buildings (see Fig. 1). The cooling effect, in form of chilled water, is produced in the plant and then distributed to individual customers through a piping network. In more advanced settings, DCS is complemented with a storage tank that is configured with the chiller plant. This optional installation increases the system's overall flexibility as cooling requirements are not required to be met by chiller plant at all points of time; rather, excess cooling effect can be produced during non-peak hours and stored for future use, especially during peak hours (Powell, Cole, Ekarika, & Edgar, 2013).

All together give a DCS the immense potential to unpack both environmental and economic benefits. Its consolidated production scheme allows tapping into the economy of scale; thus, making it a more energy efficient alternative when compared to building-specific cooling systems (Chow, Au, Yau, Cheng, Chan, & Fong, 2004). Moreover, its flexible operational conditions allows integrating various

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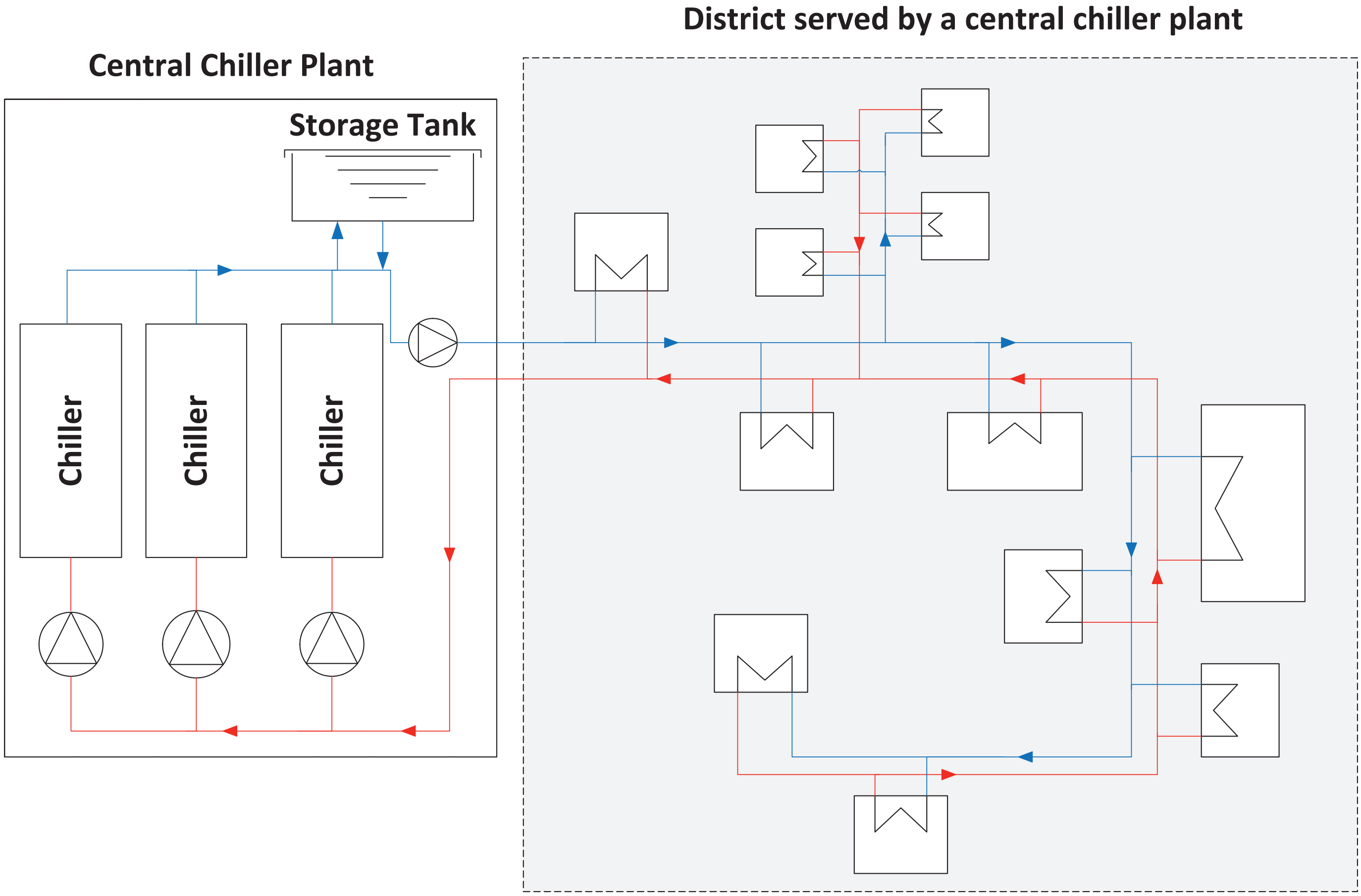

Fig. 1. Example of a DCS configuration.

cooling technologies that utilize non-carbon energy sources and environmental friendly cooling mediums such as treated sewage effluent and sea water. Hence, DCSs contribute to the reduction in pollution levels with considerable cut-off in energy-use costs (Hart & Rosen, 1996).

Even though a DCS is considered to be a long-term sound alternative, the investment costs required to build its infrastructure may hinder its adoption in some areas. It was found that 60 percent of its investment cost is attributed to the distribution network (ASHRAE Inc., 2009). This suggests that the structural optimization of a DC network is paramount and well justified. Despite this highlighted importance, the current literature dealing with the structural optimization of DCSs is relatively scant. Indeed, and unlike the great attention given to District Heating Systems (DHSs) in the operations research literature (see Aringhieri, 2003; Henning, Amiri, & Holmgren, 2006; Ming, Fenglan, & Hairui, 2012; Pinson, Nielsen, Nielsen, Poulsen, & Madsen, 2009; Rastpour & Esfahani, 2010; Sakawa, Kato, & Ushiro, 2001; 2002; Uhlemair, Karschin, & Geldermann, 2014, to quote just a few), only few studies were devoted to the optimization of DCSs. Clearly, the special characteristics observed in a DCS suggest having a customized optimization model that essentially differentiates it from any other energy distribution system. For instance, the type of cooling medium imposes certain constraints on the piping configuration. This is due to the system's thermal and hydraulic attributes such as temperature differential and pressure drop, which eventually have impact on both the design of piping network and the overall system performance.

One of the earliest attempts in the area of DC networks was pioneered by Chan, Hanby, and Chow (2007) who aimed at finding a near optimal network topology by using a modified version of the genetic algorithm (GA; Chan et al., 2007). In their study, a simplified version of the problem was addressed with the objective of minimizing both the fixed cost associated with building the piping configuration, and the pumping energy costs associated with running the plant operations. In parallel to this, relevant work was done by Soderman (2007) who developed an MIP model to find an optimal design of a DC network (Soderman, 2007). Proposed model sought to determine both structural and operational aspects of the problem so that both the annual operational and annualized investment costs are minimized. However, hydraulic- and temperature-related constraints were ignored. Likewise, Feng and Long (2008) directed their first effort to find a network layout that minimizes the total annual cost (Feng & Long, 2008). Interestingly, cooling energy losses in pipes were regarded as one of the cost parameters in their objective function. In their following study, Feng and Long (2010) utilized a standard GA to find an optimal network configuration while additionally incorporating the hydraulic stability constraints of the system (Feng & Long, 2010).

In many cases, the structural optimization of a DCS was intended to reflect the optimization of one part of the system, being the piping configuration only without considering important network design aspects presented at both the upstream and downstream ends of the system. For instance, sizing the chiller plant is an important design parameter as the capacity produced by the plant drives the whole system. This is proved by the problem that was investigated by Soderman (2007) who considered finding an optimal operating capacity for both the chiller plant and the storage tank (Soderman, 2007). Moreover, the importance of ensuring a proper integration between the network and the connected customer substations was not evident in the reviewed published works.

To stand out among the preceding few studies in the same area, we address the optimization of a DCS design while capturing

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