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Robust optimal design of district cooling systems and the impacts of uncertainty and reliability

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ABSTRACT

Uncertainty exists widely in the design of district cooling systems. Due to failures or improper maintenance of components or subsystems, the cooling systems may malfunction or work with reduced performance. In the conventional design method of district cooling systems, both aspects are often ignored or considered roughly. To ensure that district cooling systems achieve the expected performance as closely as possible, a robust optimization method is proposed in this paper. This approach relies on quantifying the uncertainty at the design stage and the reliability of the cooling system in operation. By taking the total annual cost (including the capital cost, operation cost and availability risk cost) as the objective, the robust optimal design of district cooling systems can be obtained. Uncertainties in weather, building design/construction and indoor conditions are considered and reliabilities of major equipment in the systems are dealt with as well. Individual cooling systems are often alternative to district cooling systems while uncertainty and reliability issues also exist at the design stage. The role of uncertainty and reliability in the design of district cooling systems and individual cooling systems are assessed and compared. Results show that both uncertainty and reliability have greater impacts on the design of individual cooling systems.

1. Introduction

Appropriate design and control are the key measures to guarantee high efficiency of district cooling systems (DCSs). In the conventional design method, conditions or data used at the design stage are certain values. For example, the outdoor weather conditions are usually described using a typical meteorological year (TMY) or a typical design day [1,2] for the design location. However, the actual weather in a given year can be significantly different, for instance extreme heat waves with low occurrence may not be well represented in the standard weather data. Such difference between the data used at the design stage and that in actual operation can be very significant and it should therefore be quantified and treated as uncertainty at the design stage. In fact, many other sources of uncertainty need to be dealt with when designing DCSs, such as stemming from imprecise knowledge of physical properties of individual components and the network as a whole. Another important issue to be looked at in the system design is system reliability, which refers to the capability that the system performs properly in case of certain component failures. As a consequence, the component or sub-system may not always be available due to maintenance and failures that lead to system outages [3]. The common solution is to add redundancy, e.g. by adding one or more extra groups of equipment which serve as standby. This is simple but not necessarily the best. Improved design methods need to be developed by incorporating uncertainty and reliability and thus be able to identify failure risks, outage time and the need for redundant equipment. The reliability of systems, specially related to failures, also can be regarded as a type of uncertainty. In this paper it is separated from the general uncertainties because such uncertainty has rather different numerical nature and is discrete (i.e. failed state or normal state for a component). It is addressed separately and quantified using a different method.

Concerning uncertainty and reliability issues, design methods can be classified into four groups: methods without quantifying uncertainty and reliability (*the conventional design*), methods only quantifying uncertainty (*uncertainty-only design*), methods only quantifying reliability (*reliability-only design*), and methods quantifying both uncertainty and reliability (*robust optimal design*). The conventional method determines the optimal system without quantifying uncertainty and reliability. The *reliability-only/uncertainty-only* design method moves one step forward but

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only quantifies either reliability or uncertainty and involve it into the design optimization. The design method that quantifies both aspects is regarded as the robust optimal design method, which is the target of this study. Using this method, the performance of the cooling systems can be guaranteed within certain performance tolerances, based on the probability distributions of uncertainty in the system parameters, and/or occurrence of component failures.

For the conventional individual cooling systems (ICS), several studies dealing with design optimization under uncertainty are reported in the literature [4,5]. Robust optimal design considering both uncertainty and reliability is investigated by Gang et al. [6]. For the design of DCSs, the conventional method is the most commonly used. *Uncertainty-only* and *reliability-only* design methods are not studied, not to mention robust optimal methods. Therefore a robust optimal design method is proposed and implemented in DCSs. The impacts of uncertainty and reliability on the design optimization of DCSs and ICSs are assessed and compared.

This study attempts to achieve two objectives. One objective is to propose and implement a new design method for DCSs by quantifying both uncertainty and system reliability. The other objective is to compare the impact of uncertainty and reliability on the design optimization of DCSs, and that on the design optimization of ICSs. The organization of this paper is as follows. In Section 2, studies on DCSs and applications of uncertainty and reliability quantification in building energy systems are reviewed. In Section 3, the robust optimal method and its main steps are introduced. In Section 4, a DCS is selected to demonstrate the application of the new method. In Section 5, the cooling load distribution of the DCS considering uncertainty is analyzed. The performance of the robust optimal design for the DCS is investigated. The impacts of uncertainty on the cooling loads of the DCS and ICS, and the effects of uncertainty and reliability on the design optimization of the DCS and the ICS are analyzed. Conclusive marks are summarized in Section 6.

2. Literature review

2.1. Studies and applications on DCSs

Existing studies on DCSs can be classified into the following three categories:

- *Performance assessment and comparison with conventional systems*. District cooling and heating systems in North China using seawater were compared with traditional cooling and heating systems (such as coal-fired heating system & a conventional air conditioning system, etc.) [7,8]. A district cooling and heating system in Japan was investigated and its performance was verified by comparing it with individual systems. Influential factors for the system efficiency were presented [9]. Performance assessment of DCSs is necessary at the early planning and design stages, which was investigated by several researchers [10–12].
- *Systematic optimization of design and operation*. By optimizing the location of the cooling plants, the cooling capacities of the plants, the cold storage location, the storage capacity, etc., the optimal DCS was obtained by using a mixed integer linear programming model [13]. By taking the operational planning problem of district cooling and heating plants as a mixed 0–1 linear or non-linear programming problem, the operation of district cooling and heating systems was optimized with multiple objectives using genetic algorithms, etc. [14,15].
- *Design and control optimization of chilled water systems*. Chilled water pumps in DCSs are the major additional energy-consuming parts compared with that in ICSs [10]. Therefore, design and control optimization of chilled water systems is necessary to reduce the energy consumption. This can be realized by decreasing the resistance of pipelines via adding some specific surfactants [16], optimally organizing the layout of pipelines [17,18], limiting the remote distance of consumers, adopting more reasonable pump connection ways and using a larger supply and return chilled water temperature difference [19].

Design optimization of the central cooling plant of DCSs is still not sufficiently studied yet. Any useful literature on the design optimization with consideration of uncertainty or reliability of DCSs is not found yet to the best knowledge of authors.

2.2. Uncertainty and sensitivity analysis of building energy systems

An uncertainty study can help to assess the performance of building energy systems at different risk levels by presenting the performance distributions [20–22]. The most influential factors can be identified through a sensitivity analysis. The uncertainty study is also used to improve the design or retrofit of building energy systems [23,24]. By presenting the risk and benefit distribtuions of different design schemes, stakeholders can make decisions using quantified risk measures [24–27].

For the design of building cooling systems, reliable cooling load calculation is very important since it is the basis for determining the capacity and configuration of the cooling systems. Many variables are used in the cooling load calculation and most of them contain uncertainties [5,28–30]. The peak cooling load distribution was studied by Domínguez-Muñoz et al. [31] considering uncertainties in the building material, heat transfer coefficients of external and internal wall, internal heat gain sources, etc. Hopfe [32] investigated the annual cooling/heating load considering the physical, design and scenario uncertainties. The distribution of the annual cooling/heating load and weighted over-heating/under-heating hours were analyzed. Sun et al. [5] proposed a method to size cooling/heating systems by considering uncertianties in the load calculations. Gang et al. [4] investigated impacts of uncertainty on the capacity and configuration selection of ICSs. However, studies on the uncertainty in the cooling load calculation of DCSs and corresponding impacts on the design optimization have not been reported.

2.3. Reliability assessment of building energy systems

Reliability refers to "*the probability of successful operation or performance of systems and their related equipment, with minimum risk of loss or disaster or of system failure*" [33]. Reliability design has been widely adopted in engineering of critical systems, and applied to different domains such as structures, power systems, computer science, etc. [34,35]. Reliability analysis or assessment is also concerned in the field of building energy systems. A multi-criteria approach was used to select the space heating system for an industrial building and the criteria included reliability, operational cost, comfort, etc. [36]. A method based on reliability assessment was proposed to predict an optimal inspection period for condition-based preventive maintenance for air-conditioning facilities in office buildings [37]. The expected profit produced by the method was also analyzed. Reliability assessment can be used to improve the system design, which can be found in the fields such as the power system, chemical process, etc. [33]. There is some work reported related to the design of ICSs to achieve robust optimal systems [6]. However, no application in the DCSs can be found.

3. Robust optimal design method and steps

The approach and steps of the robust optimal design for DCSs are shown in Fig. 1. In the initial stage, all variables used in the