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An uncertainty-based design optimization method for district cooling systems

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ABSTRACT

Uncertainties exist widely at the planning and design stages of district cooling systems, which have significant impacts on the design optimization. This paper therefore proposes a design method for district cooling systems by quantifying the uncertainties, which is so-called uncertainty-based design optimization method. Uncertainties in the outdoor weather, building design/construction and indoor conditions are considered. The application of the uncertainty-based design optimization method is examined in several aspects: the performance assessment, system sizing, configuration selection and technology integration. With the performance distribution at different risk levels, the design of district cooling systems can be determined by the stakeholders based on the compromise between quantified risk and benefit. Sensitivity analysis is conducted to identify influential variables with uncertainties for the cooling loads of district cooling systems. Results show that the uncertainties in the indoor condition are the most important and the uncertainties in building design/construction have the least impact.

1. Introduction

A DCS (district cooling system) generates the chilled water centrally and serves a group of buildings for cooling and dehumidification purposes [1]. It is regarded as a cooling system with high efficiency due to the concentration effect of cooling loads and the feasibility to integrate with local energy resources [2,3]. Appropriate design of DCSs is very important because it determines the capital cost, operational cost, energy usage, green-house gas emission, and thermal comfort of users. However, uncertainties exist widely in the design of DCSs and will affect the performance of DCSs. Without quantifying these uncertainties, the decision on the design of DCSs cannot be made with confidence. The performance of DCSs may fail to achieve the expectation, together with high costs and low benefits. It is therefore necessary to develop a design method for DCSs by quantifying the uncertainties at the design stage, which is the uncertainty-based design optimization method.

1.1. Studies on DCSs at the early design stage

At the early design stage, performance assessment of DCSs is required, especially when the decision is made between the DCS and ICSs (marked as conventional individual cooling systems) [4]. DCHSs (District cooling and heating systems) using seawater in China were compared with traditional cooling and heating systems (such as coal-fired heating system & conventional air conditioning system) [5,6]. Performance of a DCHS plant in Japan was verified and compared with individual systems [7]. Another important task at the design stage is the design optimization of central cooling plants. However, very limited studies are found in DCSs. Soderman [8,9] used a mixed integer linear programming model to optimize the DCS design in an urban area, including the locations of cooling plants, the cooling capacity of the plants, the cold media storage locations, etc. Chow et al. [10] tested the feasibility of using ice storage system in a DCS under a specific tariff.

All the above studies are based on certain conditions without concerning uncertainties. However, uncertainties exist generally in DCSs at the design stage. Without taking these uncertainties into account, performance of DCSs will deviate from the expectation. One case is that the capital cost of a DCS project was reported to be increased again and again because the installation cost of chilled water pipelines is much higher than the budget. Therefore, it is

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highly necessary to take uncertainties into account at the design stage and involve them into the design of DCSs.

1.2. Studies on uncertainty analysis in cooling/heating systems of buildings

Uncertainty analysis in building energy systems attracts increasing attention in the past decade. It can help assess the building energy system performance (i.e. thermal comfort, cost, energy consumption) by presenting the performance distributions at different probabilities [11–13]. It can also be used to improve the design or retrofit of building energy systems [14–17]. At the design stage of cooling/heating systems, the cooling/heating loads are the most important factors that contain uncertainties. Uncertainties in the cooling loads of one building or ICSs have been studied thoroughly [18–20]. However, uncertainties in the cooling loads of DCSs are not studied yet. Design optimization considering uncertainties was reported in building energy fields. Impacts of the uncertainties on the design of HVAC (heating, ventilation and air conditioning) systems were investigated by Sun et al. [21]. A multi-criteria design optimization method considering uncertainties for net zero energy buildings was studied by Sun et al. [22]. The design method for ICSs based on uncertainty quantification was investigated by the authors [23]. However, for the design optimization of DCSs, no studies are reported yet.

1.3. Summary of limitations of existing studies

From the above review it can be found that the work on the cooling load and central plant design of DCSs is rarely reported. No studies are found to address the uncertainties at the design stage of DCSs, not to mention to involve the uncertainty quantification into the design method. Although the design optimization method for ICSs was proposed [23], there is still large space to improve the method by considering more sources of uncertainties and adopting more reasonable samples. In addition, DCSs have unique characterises compared with ICSs and the connected buildings are often with very different functions. Another problem is that the importance of each variable with uncertainties on the performance of DCSs is still not analysed and compared. Influential variables need to be identified.

1.4. Objectives of this study

According to the above limitations, this study therefore attempts to develop a design optimization method for DCSs based on uncertainty quantification. The objectives are summarized as follows:

- An uncertainty-based design optimization method is proposed for DCSs by quantifying uncertainties at the design stage. With the proposed method, the DCS can be then designed and optimized at different risk levels. The stakeholders can make decisions based on their specific requirements.
- The method to quantify the uncertainties of the cooling loads of DCSs is developed. Uncertainties in the input variables for cooling load calculation are categorized and different methods to address these uncertainties are introduced.
- The importance of variables with uncertainties is analysed and quantified by conducting sensitivity analysis. Influential factors are identified, which provides a better understanding of these uncertainties. Attention can be paid to these influential factors to reduce the performance variation of DCSs.
- The application of the uncertainty-based design method is examined in four aspects, including the system performance assessment, system sizing, configuration selection and technology integration. The performance of DCSs using the proposed method is compared with that using the conventional method.

1.5. Organization of this paper

The paper is organized as follows. In Section 2, the uncertainty-based design optimization method is presented and detailed steps are introduced. In Section 3, methods to conduct the sensitivity analysis are presented. In Section 4, a case study on a DCS in a new district under planning in Hong Kong is introduced to demonstrate the uncertainty-based method. In Section 5, the cooling load distribution of DCSs considering uncertainties is analysed. Results of the sensitivity analysis are presented. In Section 6, performance of the DCS based on the uncertainty-based design optimization method is analysed and compared with the conventional design method. Conclusive remarks are given in the final section.

2. The uncertainty-based design optimization method and steps

The conventional method determines the design schemes of DCSs based on certain cooling loads. The inputs of the cooling load calculation use values according to the planning information, HVAC design guidelines or manuals. Sometimes, a safety factor (over 1) may be assigned to the peak cooling load to determine the capacity of DCSs. Compared with the conventional design method, the uncertainty-based method attempts to improve the DCS design by quantifying uncertainties at the design stage.

2.1. Classification of variables with uncertainties and quantification method

Many variables used in the cooling load calculation contain uncertainties. All these uncertainties can be classified into three groups based on the physical location of these variables.

1) Outdoor weather

In the conventional method, weather data of the TMY (typical meteorological year) are used in the annual hourly cooling or heating load calculation. However, the actual weather can be very different. These differences are regarded as uncertainties in the outdoor weather. Cooling loads and energy consumption of DCSs can be over-estimated or under-estimated by using the TMY data.

2) Building design/construction

At the design stage, limited information about buildings in DCSs is available, such as the gross floor area, the number of floors or the orientation. Even for such information, values used at the design stage are very hard to be the same with that actually used when the buildings are constructed. By meeting the requirements of developers or governments, the building design cannot be the same for different architects. For example, the building shapes and the material of building envelopes can vary for different architects. All these differences will affect the cooling loads and then cause energy consumption deviation. These are regarded as uncertainties in the building design/construction.

3) Indoor conditions

Internal heat gain from occupants, lighting and plug-in equipment is a primary source of the cooling load. Values of variables