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Robust optimal design of building cooling systems considering cooling load uncertainty and equipment reliability

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HIGHLIGHTS

- A new robust optimal design is proposed and developed in the HVAC field.
- Its function and performance are presented and compared with conventional methods.
- Methodology and primary technologies of the robust optimal design are presented.
- Advantages/benefits of the proposed method are demonstrated based on a case study.
- It offers a novel and efficient alternative for the HVAC system design.

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ABSTRACT

Appropriate design provides the cooling system to achieve good performance with low energy consumption and cost. Conventional design method in heating, ventilation and air-conditioning (HVAC) field usually selects the cooling system based on certain cooling load and experiences. The performance of the selected cooling system may deviate from the expectations due to cooling load uncertainty. This paper proposes a novel design method to obtain the robust optimal cooling systems for buildings by quantifying the uncertainty in cooling load calculation and equipment reliability in operation comprehensively. By quantifying the cooling load uncertainty with Monte Carlo method and chiller reliability using Markov method, the robust optimal cooling system is obtained with minimum annual total cost. By applying the new method in the design of the cooling system for a building, its function and performance as well as potential benefits are demonstrated and evaluated. Results show that the proposed method can obtain the optimal cooling systems with low cost and high robustness and provides a promising means for designers to make their best design decisions based on quantitative assessment according to their priority.

1. Introduction

In subtropical and tropical urban areas, energy consumption of heating, ventilation and air conditioning (HVAC) systems, particularly cooling systems, accounts for a large percent of the total energy consumption [1]. To reduce the greenhouse gas emission and energy consumption, it is necessary to improve the energy efficiency of building cooling systems. This can be realized by using efficient equipment/technologies and improving the design and operation of building cooling systems.

Appropriate design of building cooling systems plays a significant role for improving the energy performance of buildings since it will affect both the capital and the operational cost of buildings throughout their life cycle. Based on current engineering practice, a conventional design may follow/employ the following typical approach/methods, including:

- The full capacity of the cooling system for a building is determined under the design condition which is certain and pre-assumed in a climate region. A safety factor is assigned to the design cooling load when determining the capacity of the cooling system, considering uncertainties in the cooling load and potential cold losses.
- The number and capacity of devices (e.g. chiller, pump, cooling tower) used are determined typically based on experiences or empirical rules, by considering the year-around operation condition which is certain and pre-assumed at the design stage.

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Nomenclature

C_{total}	annual total cost of the life cycle (USD)	a_{ij}	transition intensity from state i to state j
C_c	annual capital cost of the cooling system (USD)	k	number of states for a system
C_o	annual operational cost of the cooling system (USD)	$P(t)$	probability vector of system states at time t
C_{ar}	availability risk cost of the cooling system (USD)	p_i	probability of a system at state i
CAP	capacity of the cooling system (kW)	g_i	system performance at state i
$Load$	annual cooling demand (kW)	E_∞	system mean steady performance
$CAP_{a,}$	available capacity of the cooling system (kW)	λ	failure rate
P_{ar}	price for the availability risk cost (USD/kW h)	μ	repair rate
a	number of years of a life cycle	MTTF	mean time to failure
N	working number of chillers	MTTR	mean time to repair
A	transition intensity matrix		

- Backup devices are added to ensure sufficient cooling supply in case of equipment failure or performance deterioration [2]. The backup system usually is typically determined following the rule of $n + 1$. Where n is the number of devices determined at the previous step.

Such approach/methods are effective and commonly adopted but not necessarily produce an optimal system design. Without quantifying the cooling load uncertainty and system reliability, such deterministic and empirical methods may result in large performance deviation from the design expectations and/or serious oversize problems. The oversize problems have been reported in practice and the literatures [3,4]. Therefore, it is necessary to develop a better design method to obtain a cooling system, which is appropriately sized and can always achieve good performance even when the working conditions change largely from that assumed at the design stage. Such a system is the expected output of the robust optimal design developed in this study. In fact, the concept of robust design is not new in other fields. It is defined as "*The objective of robust optimal design is to optimize the design variables such that the variation in performance, based on the variation of design variables and noise factors, becomes minimal*" [5].

In this paper, robust optimal design is proposed for the design of building HVAC systems. The objective of robust optimal design is *to achieve a cost-effective design option which provides the system the capability to operate at high efficiency at all possible conditions, particularly at partial load, through having the ability to accommodate design uncertainties and system reliabilities in operation*. Three aspects are considered in the method on the top of the above conventional method, including:

- Optimum: high efficiency of the system among all the available choices;
- Uncertainty: inequality between the actual condition in operation and the information used in design;
- Reliability: the ability of the system to perform successfully when failure happens.

Fundamental difference between the robust optimal method and other methods can be illustrated in Fig. 1. It can be seen that the conventional method determines the cooling system without quantitative uncertainty and reliability analysis. Uncertainty-based method determines the size of the systems [6] or investigates the building performance [7] considering uncertainties in design. Reliability-based method improves the system design by quantifying system reliabilities, which is rarely studied in HVAC field. Comprehensive robust optimal design method concerns quantitative uncertainty and reliability analysis as well as quantitative performance optimization simultaneously. Study and application of such a method have not yet been found in HVAC field up to now.

The concept and performance of the robust optimal design is illustrated in Fig. 2 by comparing its performance with that designed using other methods. Under normal condition (solid line): *System 1* designed using a conventional method can achieve good performance at the pre-assumed condition but the performance may drop dramatically in the presence of uncertainties (*optimal but not robust*); *System 2* is insensitive to uncertainties but its performance is not good (*robust but not optimal*); Performances of *System 3* and *System 4* remain good and stable even when uncertainties appear (*near robust and optimal*). Under abnormal condition when failure happens (dotted line): Performances of all these designs may drop dramatically while *System 4* can still retain good and stable performance. *System 4* is the robust optimal design, which is the system targeted in this study.

This paper proposes a new method to obtain the robust optimal cooling system considering cooling load uncertainty and equipment reliability. Previous studies on building energy systems considering uncertainties and/or reliabilities are reviewed in Section 2. In Section 3, the proposed methodology to realize the robust optimal design is introduced and primary technologies involved are presented. In Section 4, a case study is conducted to demonstrate the new method. In Section 5, results and performance of system designed using the proposed new method are presented and compared that using the conventional design

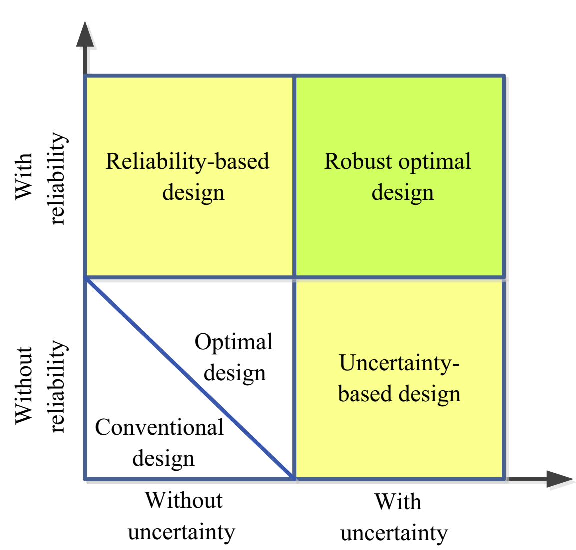

Fig. 1. Illustration of different design methods.