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HVAC system design under peak load prediction uncertainty using multiple-criterion decision making technique

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ABSTRACT

Heating, ventilation and air-conditioning (HVAC) systems are widely equipped in modern buildings to provide indoor thermal comfort and guarantee indoor air quality. In a conventional design, the components of an HVAC system are sized according to a deterministic peak load, predicted according to typical weather condition, building physics and internal load. It has been shown by many studies that this prediction is associated with uncertainties since building physical parameters cannot be accurately set and the weather and the internal load used in the design may be different from the real situation after use. Therefore, uncertainty cannot be neglected in order to properly size a HVAC system. In this paper, a prototype of HVAC system design under uncertainty is proposed, which is able to take uncertainty directly in the design, and most importantly it can assess the performance of a design at the design stage in term of multiple performance indices and the customers' requirements and preferences, i.e. the new design method falls in the framework of multiple criteria decision making. Case studies are used to illustrate the design procedure, and the result is compared with that of a conventional design method.

1. Introduction

Heating, ventilation and air-conditioning (HVAC) systems have been widely equipped in modern buildings to provide indoor thermal comfort and acceptable indoor air quality. As reported by many studies, buildings consume over 40% of end-use energy worldwide [1] and this percentage is even much higher (over 90% of electricity) in Hong Kong [2]. In large commercial buildings, HVAC systems always represent the largest primary energy end-use. There are many methods that can be used to reduce the energy consumption or improve the energy efficiency, and one efficient way among them is to size HVAC systems at design stage properly [3].

To size and configure a HVAC system for a building at the design stage, peak cooling load must be predicted [3]. The prediction can be done either according to rules of thumb (such as recommended load per unit area) or according to a typical weather condition, building physical models of heat transfer as well as a typical indoor load conditions. It is well known that this kind of prediction cannot always be accurate since the physical models of heat transfer may be inaccurate and the future weather condition and occupancy situations may be different from the typical condition [4]. Uncertainties are unavailable in the prediction [4]. Uncertainties may lead to an over- or under-sized HVAC system. As reported by many studies, an over-sized design will increase the initial cost and operational cost, and most importantly it will cause energy waste during the operation of the HVAC system [5]. An under-sized design will undoubtedly sacrifice the indoor thermal comfort during the days when the HVAC cannot provide enough cooling or heating capacity. Therefore, how to deal with the uncertainties at the design stage becomes an urgent issue.

In the conventional methods of HVAC system design, uncertainties in the prediction of the peak cooling load are handled either through *the so-called worst case scenario*, or *by adding a safety factor* [6]. In the former method, all the inputs are chosen in such a manner that they will lead to the largest peak cooling load. In the latter method, a safety factor is added to the peak cooling load that is calculated at the normal design condition [7]. These methods have been practiced for a long time. However, oversized design is still a popular problem in HVAC application [5,8]. Besides, both methods depend heavily on the knowledge and experience of designers. In order to investigate the influence of uncertainties on HVAC system design, uncertainty analysis has been developed and applied to peak load prediction and HVAC system design. For example, Fernando applied uncertainty analysis in peak cooling load calculation, finding that peak cooling load approximately follows normal distribution considering uncertainties in input parameters [9]. Christina adopted uncertainty analysis to investigate building performance, finding that energy consumption and thermal

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comfort are also uncertain when uncertainties in building parameters are concerned [10]. These researches mainly focuses on identifying the most important uncertainty sources that are associated with the peak load prediction and developing ways of reducing the peak cooling load, but lacks detail study on the influence of uncertainties on the design of HVAC systems.

To study the influence of uncertainties on the design of HVAC systems, Sun et al. [11] proposed a new framework to guide the use of uncertainty analysis (UA) and sensitivity analysis (SA) in HVAC system sizing, in which UA replaces the safety factor with quantified margins based on comprehensive quantification of different sources of uncertainty and SA is then used to identify the important individual factors or groups of factors that contribute to uncertainty. Although this work provided a mean of risk management by applying better quality assurance methods, it did not analyze the potential influence of uncertainties on the performance of the design, for example energy performance and operation cost were not deeply investigated. Essentially, when cost, energy consumption and indoor thermal comfort are concerned, the issue of sizing the HVAC system becomes a problem of multiple-criterion decision making (MCDM) [12]. Literature review reveals that multiple-criterion decision making has been widely applied in building energy management systems [13–15]. For example, Balcomb adopted the MCDM method to compare several design alternatives of the building strategies including insulation, glazing, duct leakage, thermal mass etc. [14]. Sten compared two design strategies whether adding cooling system or not in thermal zone considering uncertainties and made a choice with Bayesian decision theory [15]. Hopfe applied analytic hierarchy process to compare the performance of two buildings in terms of initial cost, architectural form, symbolism etc. [16]. However, it is found that current relevant studies focuses only on the selection of building materials that produce the least amount of cooling and heating load. The size of HVAC components under multiple criteria has not been addressed. In the proposed design approach, multiple-criterion decision making techniques will be integrated.

This paper, therefore, proposes a stochastic framework or prototype for HVAC system design under uncertainty using a MCDM technique. Under this framework, the new design approach will take account of uncertainties directly in the design produce, sizing and evaluating the HVAC system in a stochastic framework using multiple criteria. The objective is to help designers to properly size HVAC components at the design stage such that the design is able to achieve a balance among cost (initial and operational cost), energy consumption and indoor thermal comfort during the operation of the HVAC system. Potential uncertainties in the peak cooling load prediction will be investigated and modelled. Monte-Carlo simulation will be used to produce the statistic distribution of the peak cooling load. Other than simply requiring that the capacity of the designed system be larger than the peak cooling load in a predefined accumulative probability, the proposed method will evaluate the designed system in terms of multiple criteria (initial and operation cost, energy performance and indoor thermal comfort) in a stochastic framework. A case study will be used to demonstrate the design procedure and the result will be compared with that of a conventional design method.

2. Methodology

2.1. Overview of the proposed design approach

Given a building, the basic idea of the proposed design approach is shown in Fig. 1. The design procedure has basically four stages: uncertainty qualification, peak load prediction, HVAC components sizing, and multiple-criterion decision making. At the first stage, uncertainties in all input parameters for the peak load prediction, such as infiltration, ventilation, weather condition and occupant number, are considered and qualified. Those uncertainties are modelled using a statistic distribution, for example the normal distribution, the uniform distribution or the triangular distribution, to describe their uncertainty characteristics.

At the second stage, the peak cooling load is predicted using stochastic inputs and the Monte-Carlo simulation, which considers those potential uncertainties in weather, building physics and internal load. The Monte-Carlo simulation is a sample-based method which repeats model runs using random samples generated from the input distribution to predict the possible outcomes of model outputs. It is adopted because it has advantages such as simplicity of implement, applicable for complex models and different input distribution [9]. The outputs from the Monte-Carlo simulation are investigated by statistical analysis. From the statistical analysis, the characteristic of the predicted peak cooling load, such as range and occurring probability, can all be found.

At the third stage, according to customers' requirement/preferences, a performance level parameter γ is initialized to a series of values $\gamma_1, \ldots, \gamma_n$. Corresponding to each γ_i, the capacity Q of the HVAC system is determined by satisfying $(\emptyset(Q>L)>\gamma_i)$,

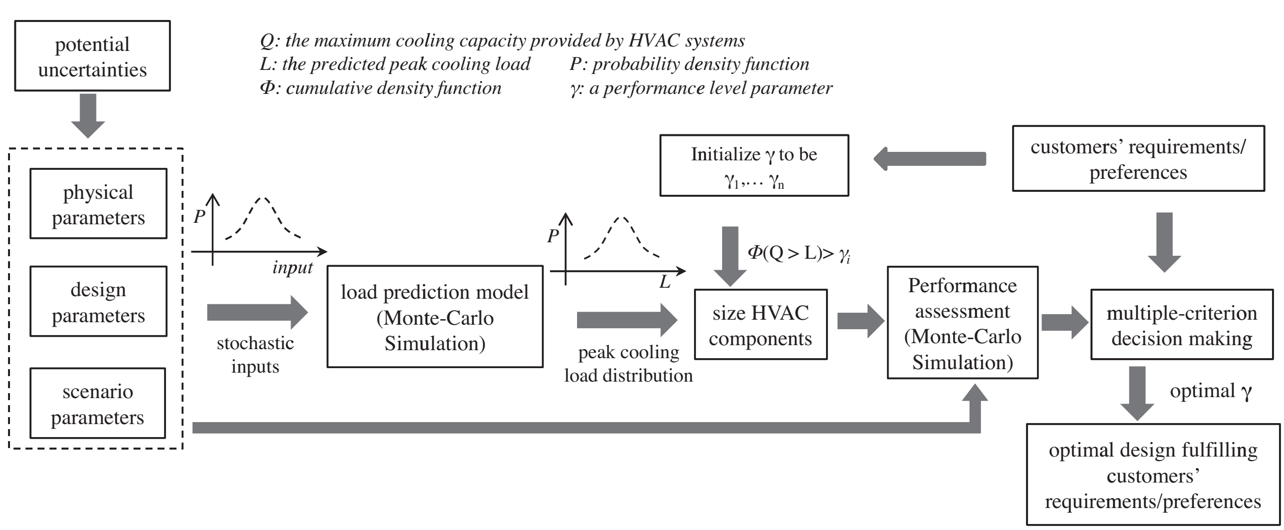

Fig. 1. A prototype of design of HVAC systems under uncertainty.