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Response-surface-model-based system sizing for Nearly/Net zero energy buildings under uncertainty

Sheng Zhang[a], Yongjun Sun[b], Yong Cheng[c,d], Pei Huang[b], Majeed Olaide Oladokun[a], Zhang Lin[b,*]

[a] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong, China
[b] Division of Building Science and Technology, City University of Hong Kong, Kowloon, Hong Kong, China
[c] National Centre for International Research of Low-carbon and Green Buildings, Ministry of Science & Technology, Chongqing University, Chongqing, China
[d] Joint International Research Laboratory of Green Buildings and Built Environments, Chongqing University, Chongqing, China

HIGHLIGHTS

- A system sizing method is proposed for nearly/net ZEBs under uncertainty.
- Response surface models are developed to evaluate performance of each design option.
- Number of Monte Carlo simulations is reduced by order(s) of magnitude.
- Proposed method robustly sorts out top 1.1% design option in expectation.

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ABSTRACT

Properly treating uncertainty is critical for robust system sizing of nearly/net zero energy buildings (ZEBs). To treat uncertainty, the conventional method conducts Monte Carlo simulations for thousands of possible design options, which inevitably leads to computation load that is heavy or even impossible to handle. In order to reduce the number of Monte Carlo simulations, this study proposes a response-surface-model-based system sizing method. The response surface models of design criteria (i.e., the annual energy match ratio, self-consumption ratio and initial investment) are established based on Monte Carlo simulations for 29 specific design points which are determined by Box-Behnken design. With the response surface models, the overall performances (i.e., the weighted performance of the design criteria) of all design options (i.e., sizing combinations of photovoltaic, wind turbine and electric storage) are evaluated, and the design option with the maximal overall performance is finally selected. Cases studies with 1331 design options have validated the proposed method for 10,000 randomly produced decision scenarios (i.e., users' preferences to the design criteria). The results show that the established response surface models reasonably predict the design criteria with errors no greater than 3.5% at a cumulative probability of 95%. The proposed method reduces the number of Monte Carlos simulations by 97.8%, and robustly sorts out top 1.1% design options in expectation. With the largely reduced Monte Carlo simulations and high overall performance of the selected design option, the proposed method provides a practical and efficient means for system sizing of nearly/net ZEBs under uncertainty.

1. Introduction

Nearly/net zero energy buildings (ZEBs) remain as promising solutions to the increasing energy and environment problems [1,2]. Buildings account for about 40% primary energy and 24% CO_2 emission worldwide [3]. Nearly/net ZEBs are characterized by a high degree of energy autonomy [4,5]. With reduced energy consumption by energy efficient technologies (e.g., ground source heat pumps [6,7] and thermal driven cooling systems [8]), nearly/net ZEBs are configured with the renewable energy system to achieve a targeted annual energy match ratio (AEMR) [9,10]. By definition, AEMR is the ratio of annual energy generation from the renewable energy system to annual energy consumption of buildings [11,12]. AEMR of a net ZEB is targeted at 100%, and that of a nearly ZEB is allowed to be less than 100% but larger than the minimal value stipulated by the policy [13,14].

When designing a nearly/net ZEB, it is challenging to properly size the renewable energy system with multiple and mutually contradictory design criteria [14,15]. Design optimization of the renewable energy

* Corresponding author.
E-mail address: bsjzl@cityu.edu.hk (Z. Lin).

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system stands as one of the major concerns in the field of nearly/net ZEBs [14]. While an under-sized renewable energy system fails to fulfill the requirements on AEMR [16], an over-sized renewable energy system leads to an unnecessary increase in its initial investment. Meanwhile, a properly sized renewable energy system is supposed to minimize the grid stress caused by the energy interaction between the nearly/net ZEBs and grid [17,18]. Due to the intermittent and fluctuant renewable energy generation and building energy consumption, nearly/net ZEBs dynamically export the surplus energy generation to the grid and import the complementary energy from the grid. To mitigate the grid stress, the renewable energy system is desired to be sized with a high self-consumption ratio (SCR) [18,19]. SCR is the percentage of the annual renewable energy generation consumed directly by the nearly/net ZEBs [20,21]. A smaller size of the renewable energy generation device could elevate SCR, but decrease AEMR, and a larger size of the renewable energy storage device could elevate SCR, but increase the initial investment.

Common methods size the renewable energy system for nearly/net ZEBs in a deterministic manner [22,23]. Firstly, the building energy generation and consumption are estimated under the worst scenario or standard scenario with a safety factor [24]. Thus, the building energy generation is under-estimated and the building energy consumption is over-estimated. Secondly, the renewable energy system is sized based on the under-estimated building energy generation and over-estimated building energy consumption. As a result, the renewable energy system is commonly oversized, with unnecessarily high initial investment and a low SCR [24,25]. On the other hand, the building energy generation and consumption are vulnerable to uncertainties associated with weather, building physical properties and etc. [26,27]. Due to these uncertainties, the actual performance of a nearly/net ZEB sized from the deterministic methods could deviate significantly from the designed performance [28,29]. For example, the real operation of an occupied ZEB in China was reported by Zhou et al. [30] that the annual energy consumption was larger than the designed value by 30.9% and the annual energy generation was smaller than the designed value by 36.8%. Attia et al. [31] comprehensively analyzed the present situations of seven European countries and pointed out that the treatment of uncertainty was a future challenge for the design of nearly/net ZEBs.

To address the problems above, the multi-criteria system sizing method for nearly/net ZEBs under uncertainty was proposed by Zhang et al. [16] and Sun et al. [29]. The multiple design criteria were weighted according to users' preference. Uncertainties in the physical, design and scenario parameters were treated with Monte Carlo simulations. An improvement of 44% in the overall performance by the optimization was reported [16]. This method was further improved by Yu et al. [32] to achieve a user-defined confidence level of the designed performance. Also, Lu et al. [15] quantified the actual performance of a nearly/net ZEB in different years under uncertainty with Monte Carlo simulations, and identified the relationship between the probability to achieve the actual performance and designed AEMR. These methods could comprehensively make trade-offs among the conflicting design criteria and harvest robust design. However, they faced a limitation of excessive computation load due to the large number of Monte Carlo simulations [33]. Monte Carlo simulations are the main technology used to treat uncertainty in the field of building energy [34,35]. To achieve the robust design of nearly/net ZEBs, existing methods conducted Monte Carlos simulations for thousands of design options [15–16,29]. For instance, Lu et al. [15] repeated 500-years Monte Carlo simulations for 2457 different design options of the renewable energy system. That is, the annual energy consumption and generation simulations of the nearly/net ZEB were repeated by 1,228,500 times (i.e., 500×2457).

To reduce the number of Monte Carlo simulations for nearly/net ZEB design under uncertainty, this paper proposes a response-surface–model-based system sizing method. The response surface methodology is an easy-to-use meta-modeling technique, which can identify the relationship between a design response and a set of design parameters based on a limited number of controlled experiments/simulations [36,37]. The identified relationship (i.e., the response surface model) reveals the effects of the design parameters on the design response. So that the design parameters could be optimally determined to achieve the most desirable design response, requiring no more experiments/simulations. The response surface methodology has been applied to the building environment design for indoor air quality and thermal comfort, such as the design of natural ventilation [38,39], underfloor air distribution [40], impinging jet ventilation [41] and other mechanical ventilation modes [42,43]. The response surface methodology has also been employed to model the building energy consumption for improved energy efficiency, including passive retrofit optimization [44], window geometry optimization [45], exergy optimization of the cooling tower [46] and optimal control of the variable refrigerant flow system [47]). However, it is unknown whether the response surface methodology could function satisfactorily for nearly/net ZEBs, due to the increased complexities from interactions among the renewable energy system, building energy consumption system and grid [14]. Kneifel et al. [48] reported that it was challenging for the meta-models to accurately predict the energy performances of nearly/net ZEBs without considering the uncertainty. Moreover, uncertainty analysis also contributes to the complexities of nearly/net ZEB design [29], which further challenges the application of the response surface methodology.

In this study, the response surface methodology will be employed to identify the relationship between the size of the renewable energy system (including photovoltaic (PV), wind turbine (WT) and electric storages [16,32]) and each design criterion (i.e., AEMR, SCR and initial investment [16,49]). With the response surface models, the overall performances (i.e., the weighted performance of AEMR, SCR and initial investment) of all the design options are calculated for decision making purposes. The establishment of the response surface models requires Monte Carlo simulations for only 29 specific design points. As a consequence, the proposed method largely reduces the number of Monte Carlo simulations, when compared with the conventional method conducting Monte Carlo simulations for thousands of design options [16,29].

With the largely reduced Monte Carlo simulations, the primary concern of the proposed response-surface-model-based system sizing method is that whether it can sort out the design option with high overall performance. This study first introduces and explains the proposed response-surface-model-based system sizing method for nearly/net ZEBs under uncertainty (Section 2). Case studies are then conducted to demonstrate the effectiveness and robustness of the proposed method in sorting out the design option with high overall performance (Section 3). The case studies consider 10,000 decision scenarios (i.e., users' preferences to the design criteria). The users' preferences in practice can significantly affect the overall performance of the finally selected design option [25]. Thus, different users' preferences should be taken into consideration to ensure the robustness of the proposed method. Lastly, several application issues of the proposed method are discussed in Section 4.

There are two main contributions of this study. (1) The response surface methodology is confirmed to work satisfactorily for the energy performances of nearly/net ZEBs. Compared with other meta-modeling techniques (e.g., the one used in Ref. [48]), the response surface methodology can generate more accurate meta-models requiring fewer data due to the utilization of the methods of Design of Experiment [50]. The effectiveness of the response surface methodology needs to be tested for different applications. Many studies are focusing on testing the response surface methodology for a specific application (e.g., modeling the thermal environment of natural ventilation [39], displacement ventilation [40], impinging jet ventilation [41] and task/ambient air conditioning system [51]). This is the first time for the response surface methodology to be tested for the energy performances of nearly/net ZEBs. (2) This study proposes a method which can