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Sensitivity analysis of design parameters and optimal design for zero/low energy buildings in subtropical regions

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HIGHLIGHTS

- A new approach for design optimization of zero/low energy buildings is proposed.
- The approach integrates multi-stage sensitivity analysis and design optimization.
- An optimization method for buildings without heating in subtropics is developed.
- Concern of winter thermal discomfort affects the selection of key design parameters.
- Such concern affects the optimal design of buildings without heating in subtropics.

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ABSTRACT

To reduce building energy use and mitigate CO_2 emissions, zero/low energy buildings have attracted increasing attention. However, the impacts of the main design parameters and optimal design for zero/low energy buildings only provided with cooling in subtropical regions are seldom studied, and the objectives for building performance assessment and design optimization in such particular situations are not addressed sufficiently. In this study, the impacts of the main design parameters and optimal design for zero/low energy buildings in subtropical regions are studied. A holistic approach integrating sensitivity analysis and design optimization is developed for zero/low energy buildings. A new optimization objective is proposed, which considers annual energy consumption and winter thermal discomfort, for buildings without heating provision. A multi-stage sensitivity analysis approach is proposed to identify the key design parameters for design optimization. The key building design parameters are optimized to minimize the optimization objective using the genetic algorithm. A case study is conducted, using the zero carbon building (ZCB) in Hong Kong as a reference building, to illustrate the implementation steps and effectiveness of the proposed approach. This paper presents the identification of the key influential design parameters in the subtropical climate and the design optimization method of zero/low energy buildings as well as the procedures and the results of the case study.

1. Introduction

Energy conservation and environmental protection are among the most critical issues faced by the sustainable development of human societies. Buildings play very significant roles in mitigating these issues as they account for over 40% of end-use energy in the world [1] and this percentage is even much higher (i.e. 80% of end-use energy and 90% of electricity) [2] in Hong Kong. In order to reduce building energy consumption, zero/low energy buildings are becoming increasingly attractive [3–5]. Many efforts have been made on the design for zero/low energy buildings. The design involves two major tasks: building envelope design and energy system design. This study only focuses on the building envelope design of zero/low energy buildings. Three main aspects of the building design are addressed in the previous studies: (1) energy-efficient technologies [6]; (2) impacts of the main building design parameters [7–23]; (3) building design optimization [24–37]. The main energy-efficient technologies have already been explored thoroughly by researchers, which mainly include thermal insulation, thermal mass, window area, glazing, building orientation, reflective/green roof and shading [6]. In recent years, many researchers are concerned about the impacts of the main design parameters in different climates and their design optimization. *The impacts of main design parameters and climate/site*: The impacts of the main building design parameters in different climates/sites have been studied by many

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Nomenclature

F	performance objective (J)
E_{tot}	annual total electricity consumption (J)
E_{ele}	annual electricity consumption of lighting and other equipment (J)
Q_{cool}	annual cooling demand of building (J)
D_{dis}	hourly discomfort index
a	penalty ratio of discomfort (J)
COP	overall coefficient of performance of air-conditioning system
PMV	predicted mean vote
U_T	overall wall U value including thermal bridge (W/(m^2 K))
U_0	wall U value (W/(m^2 K))
A_{tot}	total opaque wall area (m^2)
L	total length of linear thermal transmittance (m)
ψ	linear thermal transmittance (W/(m K))
χ	point thermal transmittance (W/K)

researchers and the results show that the highly-sensitive parameters of building thermal performance are different in different climate regions as listed in Table 1 [7–23]. The internal loads, infiltration and temperature set-point of heating, ventilation and air-conditioning (HVAC) systems were proven to be the highly-sensitive parameters concerning the building thermal performance in all climate regions [7–10]. Thermal insulation of external walls is important for buildings in the climate regions with cold winter [8,10,11], while window area, glazing and solar protection are very influential to building energy consumption in the climate regions with hot summer [7–9,11]. For buildings in the climate regions with mild seasons, natural ventilation can make a great contribution to reducing the building cooling demands [12]. However, there are two limitations in the existing studies. First, only one sensitivity analysis method is usually adopted to assess the design parameters which may lead to the missing of important design parameters. Yang et al. [13] recommended that at least two fundamentally different sensitivity analysis methods should be performed to provide more robust results. The second is that sensitivity analysis often does not comprehensively address design parameters and the identification of key design parameters since many other non-design parameters are involved.

Building design optimization parameters and methods: The commonly optimized parameters are insulation thickness of the external walls, building orientation, window to wall ratio (WWR), glazing type, and external shading [24–37]. The parameters/design are generally optimized using two approaches. The typical approach adopted in the old days can be regarded as “local design optimization” which optimizes individual design parameter one-by-one [24]. The typical approach adopted in recent years can be regarded as “global design optimization” which optimizes all the concerned design parameters at the same time to identify the optimal set of the design parameters. The first approach has its limitation that the obtained design options may not be the optimum since it ignores the correlation and interaction between the design parameters. The second approach can overcome this drawback. The genetic algorithm (GA) is the most favorable global optimization method [25]. So far, most building design optimization studies focus on the regions with cold winters probably because of the government policy (e.g. European initiatives) and the urgency for the cold regions to reduce building energy consumption. The envelope design optimization of zero/low energy buildings without heating in subtropical regions is seldom studied. Most studies on the design optimization for zero/low energy buildings in subtropical regions focused on building energy systems [38–43]. In addition, the design parameters are determined mainly based on experiences and previous impact studies in similar climate regions. Very few researchers addressed sensitivity analysis on design parameters and design optimization comprehensively.

Building performance and design optimization objectives: The commonly-used building design optimization/performance objectives are building energy consumption (including cooling/heating load), thermal comfort and life cycle cost. Concerning the performance objectives, optimization can be classified into single objective optimization and multi-objective optimization. Wang et al. [26] applied multi-objective genetic algorithms to a green building design optimization. Yu et al. [27] studied the low-energy envelope design of residential buildings in the hot summer and cold winter zone of China. Pikas and Thalfeldt et al. [28,29] studied the cost optimal fenestration (window size and glazing type) design solutions for a nearly ZEB. No comprehensive objectives have been found to assess both energy performance and thermal comfort for buildings without heating.

In this study, the impacts of main design parameters and optimal design for zero/low energy buildings without heating provision in subtropical regions are studied. A holistic approach integrating sensitivity analysis and design optimization is developed for zero/low energy buildings. A new optimization objective is proposed, which comprehensively considers annual energy consumption and winter thermal discomfort in buildings only provided with cooling in subtropical regions. A multi-stage sensitivity analysis approach is adopted to identify the key design parameters for design optimization. The key design parameters of buildings are optimized to minimize the performance objective, using the genetic algorithm. A case study, using the zero carbon building (ZCB) in Hong Kong as the reference building, is conducted to study the impacts of main design parameters and optimal design for zero/low energy buildings in subtropical regions, which are provided with cooling only. The methods and steps of the sensitivity analysis and design optimization, the identification of key design parameters in subtropical regions and the design case study are presented in this paper.

2. Methods and procedures of building design optimization

2.1. Outline of the holistic design optimization approach

The proposed holistic approach integrates a comprehensive sensitivity analysis and design optimization for the optimal design of zero/low energy buildings. At first, a multi-stage sensitivity analysis is conducted and the impacts of the main design parameters on performance or design objective are studied to identify the key envelope design parameters for building design optimization in the specific condition concerned, such as the climate condition. Then design optimization is used to optimize the identified key design parameters and achieve the optimal design with the minimum performance objective. Where, the performance objective value of each scenario in the sensitivity analysis or each design option in the design optimization is quantified by building performance simulation.

2.2. Building performance quantification method

EnergyPlus [44], a commonly-used building simulation software, is applied for building performance quantification in this study. In general, free energy sources, such as natural ventilation and daylight, are taken into full consideration in the design of zero/low energy buildings in order to satisfy the low energy requirement. Therefore, the control logic, adopted by EnergyPlus for the building performance simulation and quantification in this study, is set to maximize natural ventilation and daylight in order to minimize building energy consumption while maintaining an acceptable thermal comfort as far as possible. This simulation control logics concerning the uses of natural ventilation and daylight are described here below.