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# Sensitivity analysis of energy performance for high-rise residential envelope in hot summer and cold winter zone of China

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ABSTRACT

Building envelopes are the interface between indoor and outdoor environment which affect the indoor heat gain and heat loss in the design of sustainable buildings. It is beneficial to identify the most important design parameters in order to develop more efficiently alternative design solutions. This study performs a sensitivity analysis of energy performance to assess the impacts of envelope design parameters and identify the important characteristics. Index of evaluation on energy and thermal performance (EETP) for residential envelops is introduced for the calculation of energy use. High-rise residential buildings with small and large window-to-wall ratio (WWR) are selected in four cities of hot summer and cold winter zone of China. Eight design parameters of envelope are analyzed and compared. Results show that: in cooling season, shading coefficient and WWR are the most vital factors; in heating season, wall heat-transfer coefficient and shape coefficient have crucial effects when WWRs are 25% and 50%, respectively; for annual energy use, wall heat-transfer coefficient and WWR are the most sensitive when WWRs are 25% and 50%, respectively; whether the WWR is small or large, solar absorptances of wall and roof and heat-transfer coefficient of roof have very slight effects.



## 1. Introduction

Buildings, energy and environment are the key issues facing the building professions worldwide, and energy is a key element in the overall effort to achieve sustainable development [1]. In hot summer and cold winter zone of China, energy use of residential buildings has been increasing sharply over the last 10 years; there is a growing concern about the energy use in residential buildings. The climate here is extremely severe in both summer and winter, the average temperatures of the hottest month and coldest month are 25–30 °C and 2–7 °C respectively, which are about 2 °C higher and 8 °C lower than the same latitude all over the world [2]. Additionally, the thermal-insulating level for residential buildings is extremely poor. Single-clear glazing, clay brick wall and non-insulated roof are wildly used in the existing residential buildings, and more than 95% of new ones are high energy intensity buildings [3]. With the improvement of people's living standard, the numbers of air-conditioned buildings and the amount of energy use in these buildings have increased dramatically in recent years. Building envelopes are the interface between indoor and outdoor environment which affect the indoor heat gain and heat loss. One way to alleviate the ever growing demand for energy is to have more energy-efficient building designs and proper building energy conservation measures [4]. The national standard for energy efficiency of residential buildings is launched with the target of a 50% reduction in energy use compared with that of a base building under the same indoor thermal conditions, about 30% of reduction is projected to be achieved by building envelope [5]. Energy conservation of residential envelope is therefore becoming one of the major issues of concern to the local government.

In an energy-efficient building, heat gain and loss through building envelope should be minimized [6]. The control of thermal performance of the building envelope is an important part of the overall scheme for building energy conservation. If the relationships and relative importance of envelope design parameters are well understood, we will be able to achieve the optimum building energy performance through proper selection of design variables. A sensitivity analysis makes it possible to identify the sensitive parameters in relation to energy performance and optimization of sustainable building. In the field of building energy models, combining sensitivity analysis with simulation tools can be useful as it helps to rank the input parameters and then to select the most important ones to be considered. This information is useful to help managers and

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engineers identify energy saving potentials and evaluate energy performance of the energy efficiency measures to be implemented.

Different parameters lead to various optimal results directly; some researchers have studied the sensitivity analysis of energy and thermal performance of the buildings. Lam and Hui [7] examined the sensitivity of energy performance of office buildings in Hong Kong, 12 input parameters were studied which were categorized into building load, HVAC system and HVAC refrigeration plant. It has been found that the annual building energy use and peak design loads were sensitive to the measures affecting internal loads, window system, temperature set points and HVAC plant efficiencies. Tavares and Martins [8] conducted a sensitivity analysis of several parameters of a public building at the center region of Portugal, relating to wall and roof structure and materials, window frames, shading system, infiltration, mechanical ventilation, HVAC system, design temperatures and thermostats set-point. Corrado and Mechri [9] analyzed the heating and cooling needs of a two-storey single-family house in Turin with sensitivity analysis to calculate the uncertainties in energy rating. The sensitivity analysis showed that only 5 of 129 factors were responsible for most of these uncertainties: the indoor temperature, the air change rate, the number of occupants, the metabolism rate and the equipment heat gains. Heiselberg et al. [10] identified the most important design parameters in relation to a building's performance with focus on the optimization of an office building in Denmark through sensitivity analysis. They found that the mechanical ventilation rate in winter and lighting control were the most influential parameters in an office building. Breesch and Janssens [11] proposed the uncertainty and sensitivity analysis to evaluate the performance of different natural night ventilation designs and their relation to building design using the simulation code of TRNSYS-COMIS. Tian and Wilde [12] explored the uncertainties and sensitivity coefficients in the prediction of thermal performance of the buildings under climate changes, and a case study focusing on an air-conditioned university building at the campus of the authors was presented. Wang et al. [13] carried out the sensitivity analysis to guide the optimal design of the building cooling heating and power system and improve the robustness of the optimal results, the influences of the technical, economic and environmental parameters on the optimal results were analyzed and compared.

Several studies have investigated the energy performance in sustainable design of residential buildings in hot summer and cold winter zone of China. These studies largely focused on the energy savings potential and energy performance of certain measures using energy simulation programs, such as the effects of shape coefficient [14,15] and WWR [16,17] on annual energy use, the relationship between insulation thickness and air conditioning load [18], the determination of optimum insulation thickness over the lifetime [19,20], the thermal performance of external windows/skylights [21,22] and shading system [23]; some focused on the low-energy envelope design and the comparison of energy performance based on a reference building using some strategies [24–26]. There are few studies published about the sensitivity analysis of envelope design parameters on the overall building energy performance in hot summer and cold winter zone, which can quantitatively explain the effect of each parameter of building envelope on the energy use under given circumstances and identify the important design parameters in order to reduce the energy use in residential building.

In response to the growing concerns about energy conservation in residential envelopes, some evaluation indices on the energy and thermal performance of envelopes have been carried out, which are able to help ensure cost-effective energy efficiency opportunities incorporated into the new buildings and achieve the sustainable building designs, such as the Overall Thermal Transfer Value (OTTV) for wall and roof [27] and the Envelope Thermal Transfer Value (ETTV) [28]. An index of evaluation on energy and thermal performance (EETP) for residential envelopes was proposed by our earlier work, which can be used as a simplified energy calculation method [29]. The primary aim of the present work is to conduct the sensitivity analysis of energy performance for high-rise residential envelope in hot summer and cold winter zone of China by a series of energy use calculations using EETP index, which delivers the pieces of information to architects and engineers involved in the design of high-rise residential building envelopes. The cities selected to represent A, B, C and D sub-zones are shown in Table 1; the present work involved the followings:

**Table 1**
The selected cities in hot summer and cold winter zone.

| Subzone | Determination of subzones | Typical city |
|---|---|---|
| A | 1000 °C d ≤ HDD18 < 2000 °C d, 50 °C d < CDD26 ≤ 150 °C d | Shanghai |
| B | 1000 °C d ≤ HDD18 < 2000 °C d, 150 °C d < CDD26 ≤ 300 °C d | Changsha |
| C | 600 °C d ≤ HDD18 < 1000 °C d, 100 °C d < CDD26 ≤ 300 °C d | Shaoguan |
| D | 1000 °C d ≤ HDD18 < 2000 °C d, CDD26 ≤ 50 °C d | Chengdu |

(1) The sensitivity analysis method is presented to determine the contribution of an individual design parameter to the energy performance of the envelope design solution; EETP index is introduced for the calculation of cooling and heating energy use. The high-rise base case building with small and large WWRs is described.
(2) Sensitivity analysis of energy performance for high-rise residential buildings in hot summer and cold winter zone is performed, the sensitivity coefficient is calculated and analyzed by observing the response of annual building energy use calculated by EETP index due to the changes in input envelope design variables, including the building shape coefficient, WWR, heat-transfer coefficients of roof, walls and windows, solar absorptances of external wall and roof and shading coefficient of glazing.
(3) The impacts of input envelope design parameters are estimated and the important characteristics of input variables are identified from point of view of annual building energy use, the energy saving potentials of energy conservation measures are illustrated.

## 2. Methodology

### 2.1. Sensitivity analysis

A sensitivity analysis determines the contribution of an individual design parameter to the total performance of the design solution and makes it possible to identify the most important design parameters for building performance. Sensitivity coefficient is used to assess the impact degrees of input parameters on the output, which is defined as a ratio of the percentage change (with respect to the base case value) in output (annual energy use) to the percentage change in input design parameter, it can be expressed as follows [30]:

$$S_i = \frac{(\Delta L/L_n)}{(\Delta P_i/P_{i,n})} \tag{1}$$

where $S_i$ is the sensitivity coefficient, $\Delta P_i$ is the variation of input design parameter, $\Delta P_i = P_i - P_{i,n}$; $P_i$ is the value of input parameter $i$, $P_{i,n}$ is the base value of each input parameter $i$; $\Delta L$ is the output variation for the change of input parameter, $\Delta L = L_i - L_n$; $L_n$ is the output value of the base case, $L_i$ is the output when the value of