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Parametric study of passive design strategies for high-rise residential buildings in hot and humid climates: miscellaneous impact factors

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ABSTRACT

This paper focuses on the application of sensitivity analysis (SA) to typical passively designed high-rise residential buildings in hot and humid climates by considering multiple indoor environmental indices and impact factors. The sampling based Monte Carlo Analysis (MCA) is adopted to carry out multiple regression analyses between selected input parameters and output indices. Input parameters including the building layout, envelope thermophysics, building geometry and infiltration &$2 air-tightness extensively cover each aspect of passive design strategies to improve the sustainability of buildings, while miscellaneous output indices represent major indoor environment factors such as lighting, ventilation and thermal comfort conditions addressed by the local green building guidance. A dynamic simulation program generates all required outputs based on input parameters by constructing a generic building model with different assumptions of internal loads, ventilation control methods, running periods and weather conditions. The calculated sensitivity indices on different output indices chances with simulation control variables, whereas the window solar heat gain coefficient and window to ground ratio are consistently among the most influential design factors. In addition, ASHRAE Adaptive Comfort Standard with 90% Acceptability is determined to be the most adequate assessment method of the building thermal comfort in hot and humid climates similar to Hong Kong. This proposed SA approach accounts for most identified impact factors in a passively designed building and can therefore help conceive potential sustainable solutions in early architectural design stages.

1. Introduction

The process of green building design requires the project team to constantly hold in mind the building performance in respect of the energy efficiency, material use, indoor environment quality and so forth. It takes much less resources to have a major impact on these aspects if start taking initiatives from the earliest design stage. Fig. 1 describes potential sustainability impacts relative to the cost of efforts in various stages of a building project, where impacts reduce as the design and construction proceed [1]. To achieve a green or sustainable goal in building projects, designers and engineers can consider exploiting passive design features including the building layout, envelope thermophysics, building geometry and infiltration &$2 air-tightness, which have been proved to significantly affect the building performance in many studies [2–6]. Simply using these passive strategies is not enough to realize the sustainable design target. A holistic optimization process based on in-depth and exhaustive sensitivity analyses (SA) is essential for designers to understand the relative importance of each strategy and deploy them appropriately at the first opportunity. Building design factors can be examined by different SA approaches with the assistance of building simulation tools. In this article, SA applications in passive designs and research methods in respect of miscellaneous inputs, outputs, control variables and modelling algorithms are extensively examined. The most influential parameters and appropriate indoor comfort evaluating indices for typical high-rise residential buildings in hot and humid climates are determined. Statistical inferences from the SA results can also contribute to future building performance optimizations.

2. Review of SA application in building passive designs

Sensitivity analysis (SA) has been applied to the building performance estimation and optimization in many aspects, including but not limited to the building design, validation of energy models, impact of climates and life-cycle analyses [7–9]. The main differences among the these applications lie in the determination of input factors and their

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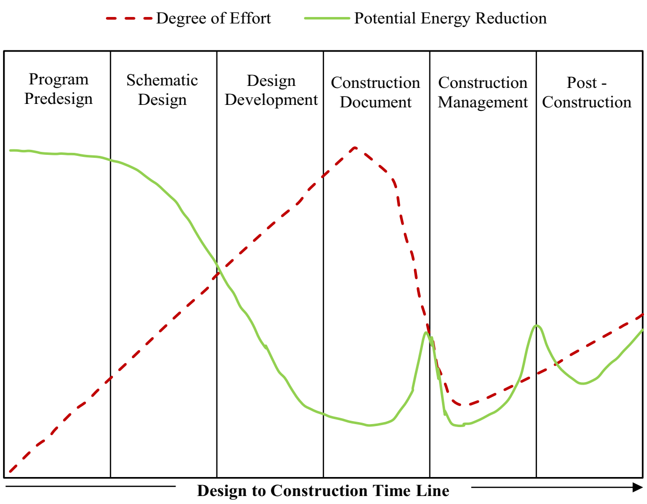

Fig. 1. Impact of input efforts through design and construction stages on building energy performance.

variations, constructing building models, sensitivity analysis methods (including sampling and regression algorithm) and interpretation of output indices. As the input variables in this research are limited to the passive design strategies, the following literature review will focus on the remaining three application differences.

2.1. Building models

SA has been conducted to observe impacts of variable input conditions in both domestic and commercial buildings [10–12]. Building modelling is usually concerned with the envelope characteristics, occupancy gains, equipment loads and infiltration rate, whereby natural ventilation becomes an effective strategy to promote the indoor air quality, thermal comfort and energy conservation [13–15]. In most SA studies [10,16,17], the natural ventilation rate is set as model inputs instead of calculated outputs, leading to a possible misinterpretation of SA results because of its high correlation with other design factors. In hot and humid climates where natural ventilation alone cannot satisfy the indoor environmental comfort, mixed-mode (MM) ventilation with auxiliary air-conditioning systems is coupled to the building model [18,19]. A detailed sensitivity analysis based on the total energy consumption of a single-family building deduced a three-parameter change-point regression model to identify any energy efficient measure in the house design [20]. In this calibrated simulation, air-conditioners are not activated until a specified cooling-change point temperature is reached. Influential parameters of high-rise residential buildings in all Chinese climate zones were studied by assessing the percentage change of energy demand deviation from the base case [21]. Identified three most influential factors for each climate zone were modulated to achieve energy saving and indoor thermal comfort. Furthermore, the socio-demographic model and behavior model were also combined with the building physical and system model to better explain the annualized energy consumption in residential buildings [22]. In this study, energy performance in residential buildings was explained in a stock level, while retrofitting and behavior changing initiatives were proved to be less important for energy reduction compared with the building physical size.

2.2. Sensitivity analysis methods

The local sensitivity analysis, also known as the differential method which changes one input variable at a time, is used to examine the energy performance of office buildings in Hong Kong with DOE-2 as the simulation tool [23]. Input factors regarding building loads, HVAC systems and refrigeration plants were independently varied against three different model outputs. The building model made reference to the local practice, while the lighting load, thermal set point and chiller coefficient of performance were proved to be the most influential factors in three input groups respectively. Instead of the whole building sensitivity analysis, the building envelope was solely investigated to decide the optimum slab thickness for floors, ceiling and external walls by considering the thermal mass effects on the indoor operative temperature. The maximum window to wall ratio for the envelope was also determined by a function of the diurnal temperature amplitude [24]. The window aperture area was also independently correlated with the peak electricity demand and annual energy consumption to provide simple design charts for engineers in early planning stages [25].

Apart from the above local sensitivity studies, the global sensitivity analysis, in which all input variables are changed at the same time, is adopted to evaluate the uncertainty and sensitivity of a passively cooled office building in a moderate climate [26]. The research investigated influences of single-sided ventilation, passive stack and cross ventilation strategies over indoor thermal comfort levels. According to the findings, the indoor thermal comfort was mostly perturbed by the single-sided ventilation yielding the largest uncertainties. In addition, global warming was proved to increase the uncertainty in thermal comfort, as the natural ventilation strategy is rather sensitive to the outdoor conditions. The Global SA in building applications mostly adopts sampling-based Monte Carto Analysis (MCA) with multiple regression method to assess the sensitivity of miscellaneous input parameters [16,17,26]. The Standardized Regression Coefficient (SRC) or Standardized Rank Regression Coefficient (SRRC) is applied to linear or non-linearly correlations to estimate the relative importance and ranking within the input matrix. Based on findings from a previous research work [27], the prediction of local SA deviates from those of global SA especially when the relationship between the input and output is nonlinear and parameters vary in different orders of magnitudes.

2.3. Sensitivity output indices

In abovementioned sensitivity studies, heating loads and cooling loads are commonly used as output indices on which design factors such as the total window area, heat transfer coefficient and solar heat gain coefficient were proved to have major impacts. The energy demand and indoor temperature fluctuation can thus be minimized by modulating important input factors such as the building shape factor, envelope thermal resistance or occupant behavior [28–30]. Besides, building energy consumption, peak design load and load profiles are also identified as typical output indices in global and local SA investigations for different types of buildings [31,32]. The weighted temperature excess hours (WTE) based on the predicted mean vote (PMV) comfort standard were unusually used as the output index for a naturally ventilated office building to obtain the most influential factors in the unstable outdoor wind environment [26]. The study provided a new angle to conduct SA on indoor environmental outputs.

According to the above review, it can be summarized that there are few sensitivity studies on passive design elements of high-rise residential buildings with indoor environmental outputs in hot and humid climates. Such studies should involve demonstration and validation with controlled modelling scenarios and extensive assessment indices, where this work mainly contributes.

3. Research design for sensitivity analysis

The proposed sensitivity analysis (SA) approach in this study targets to explain the variance of each specified model output in relation to major passive design strategies. A typical SA usually consists of selecting input variables, creating models, running models, collecting simulation results, conducting sensitivity analysis and interpreting