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Sensitivity analysis and optimization of a typical passively designed residential building with hybrid ventilation in hot and humid climates

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Abstract

Passive design strategies are preferable for constructing low-energy buildings given their significant influences on the building energy consumption. The building layout, envelop thermophysics, building geometry and infiltration & air-tightness are major considerations of the passive design to achieve building sustainability. In this paper, modelling experiments on a generic residential building in hot and humid climates are conducted to integrate a robust variance-based sensitivity analyses with an early-stage design optimization process. Daylight, ventilation and thermal conditions are simulated with EnergyPlus to obtain the total lighting and cooling energy consumption under the hybrid ventilation and daylight dimming control algorithm. The non-dominated sorting genetic algorithm (NSGA-II) is then coupled with the modelling experiment to obtain the Pareto frontier as well as the final optimum solution. Furthermore, different settings of NSGA-II are investigated to improve the computational efficiency of the optimization process. Findings from this study will guide decision-makers through a holistic optimization process for energy-saving targets in a passively designed green building.

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Keywords: Passive design; Sensitivity analysis; Optimization; NSGA-II; Green building

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1. Introduction

Over 60% of the total energy use in Hong Kong is attributed to building sectors as per statistics published by the local government [1]. To approach low energy or zero energy buildings, local building design codes and green building rating schemes (i.e. BEAM Plus) have been updated frequently to address the state-of-art of sustainable technologies, among which passive design is attracting more attention because of its proved effectiveness on improving the cooling and lighting performance of buildings [2-4]. As space cooling and lighting consume a major part of household energy end use, passive design features including the building layout, envelop thermophysics, building geometry and infiltration & air-tightness can make great contributions to achieve above energy saving targets. Integration of these passive strategies requires not only understanding their individual impacts on building performance, but also conducting a holistic design approach by incorporating their interactive effects [5, 6]. It is essential for architects and engineers to understand the relative importance of each strategy and deploy them appropriately at the first opportunity.

Building design factors can be subject to systematic sensitivity and optimization studies with different statistical methods and simulation tools. The glazing area, shape coefficient, envelope thermal resistance and occupant behaviour pattern the building energy demand were individually adjusted to validate their respective impacts on building performance in early planning stages. Instead of adopting local SA methods (i.e. modulating one design factor at a time), the global SA can study building performances with the regression-based, screening-based and variance-based methods [7]. Based on identified influential design variables from sensitivity analyses, building design optimization can be further conducted to improve its life-cycle cost effectiveness, energy efficiency and indoor environment qualities. Energy performance optimization with the Multi-island Genetic Algorithm (GA) was performed by a software platform developed with the QT language and OpenGL interface [8]. Besides genetic algorithm (GA) methods, the multi-objective particle swarm optimization (MOPSO) algorithm was exploited to search for Pareto optimal solutions for a generic room model under different weather conditions of Iran [9]. Furthermore, simultaneous optimizations by the Hooke-Jeeves Algorithm, Multi-objective Genetic Algorithm-II and Multi-objective Particle Swarm Optimization Algorithm were conducted to explore building design performance in terms of the stability, robustness, validity, speed, coverage and locality [10].

According to the above brief introduction and literature review, it can be recognized that there is little research in combined sensitivity and optimization analyses of passively designed buildings in hot and humid climates under hybrid ventilation conditions. This paper mainly focuses on the energy efficiency optimization of single-side ventilated building with selected significant input design variables based on a comprehensive sensitivity analysis. Simulation models were coupled with NSGA-II to obtain the Pareto frontier as well as the final optimum solution under different control algorithm settings.

2. Methodology

2.1. Passive architectural design factors

Input variables to the building simulation are limited to passive design parameters in this research. The building layout includes the external obstruction angle (EOA) which measures the external shading effects from 0 to 87 degrees as per shadings in a street canyon and building orientation (BO) altered in the modelling experiment within the range of 360 degrees. The external wall thermal resistance (WTR), specific heat (WSH), window U-values (WU) and solar heat gain coefficient are involved to represent the envelop. WTR changes from a baseline equivalent thermal resistance of 0.09 m^2 K/W to a highly insulated one of 10.56 m^2 K/W as suggested by the 2009 ASHRAE Handbook-Fundamentals. WSH changes from 800 to 2000 J/kg K as typical values in EnergyPlus modelling guidelines. The window thermal properties changes from a triple-vacuum low emissive glazing (i.e. SHGC=0.1 and U-value=0.2) to a clear single glazing (i.e. SHGC=0.9 and U-value=6.0 W/m^2 K). The window to ground ratio (WGR) varying between 10% and 50% and overhang projection fraction (OPF) subject to a maximum of 0.56 (by plot ratio limitations) are further investigated under the category of the building geometry. At last, the infiltration & air-tightness is evaluated by the infiltration air mass flowrate coefficient (IAMFC) of the crack on external wall surfaces. The allowable range between 0.01 and 0.03 kg/s represent the scenarios from infiltration to ventilation in the simulation. The abovementioned input variables are uniformly sampled as non-informative distributions to evaluate their relative impacts on the building energy efficiency.

2.2. Definition of simulation setting and performance indicator

A generic building model is constructed in EnergyPlus to represent a typical high-rise building developed by the Hong Kong Housing Authority. The building is modularly designed with a standard floor layout plan as shown in a previous work [11]. Each flat is assumed to be occupied by two people with average activity levels of 100 W/person (i.e. between seated and sleeping). The lighting and equipment load levels as well as building operation schedules are referenced to the BEAM Plus guideline and the Building Energy Code [12]. The cooling and lighting energy consumption is derived from interlinked sub-modules of the daylight, airflow network and HVAC systems in EnergyPlus. A simplified HVAC system is chosen to maintain the indoor thermal comfort condition when natural ventilation alone cannot meet the requirement. The single cooling set point controller is used as the thermostat to comply with the upper limit of the ASHRAE55 adaptive comfort model, which varies monthly with the prevailing outdoor air temperature. Control of hybrid ventilation is executed to maximize the benefit of deploying passive design strategies, and the overall framework is presented in Fig. 1.

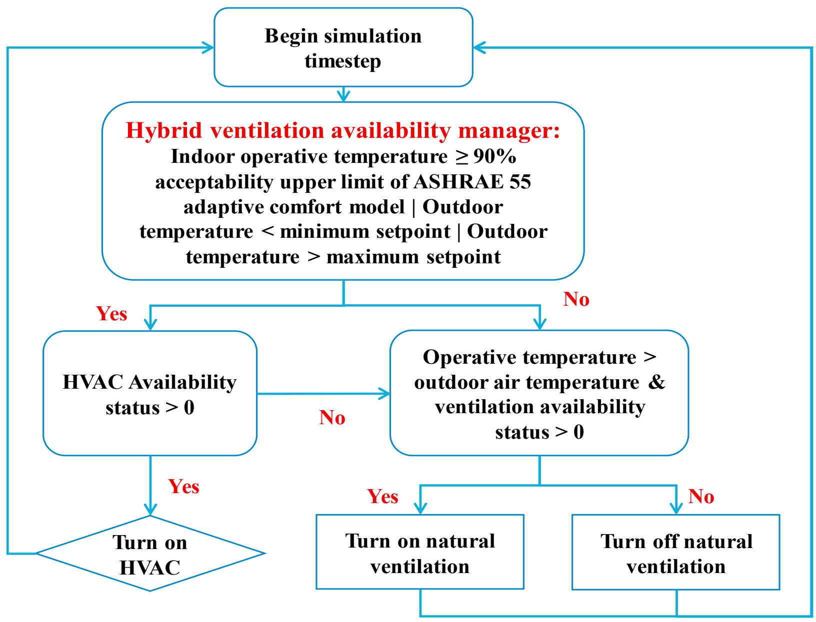


Fig. 1. hybrid ventilation operation flowchart

2.3. Variance-based sensitivity analysis and multi-objective optimization

The variance-based method is chosen to conduct the initial sensitivity analysis, where the total variance of the output is decomposed as Eq. (1):

$$V(Y) = \sum_{i=1}^{k} V_i + \sum_{j>i}^{k} V_{ij} \cdots + V_{12\cdots k} \tag{1}$$

The relationship between different orders of sensitivity indices can be obtained from:

$$1 = \sum_{i=1}^{k} S_i + \sum_{j>i}^{k} S_{ij} + \cdots + S_{12\cdots k} \tag{2}$$

where the S_i is called the first-order sensitivity index, which stands for the independent impact of changing X_i on the variance of Y. The total sensitivity index summarizing the all orders of sensitivity indices are expressed by Eq. (3).

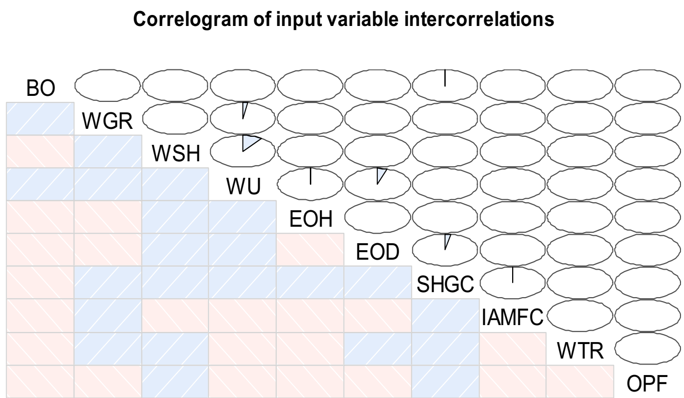
$$S_{Ti} = S_i + \sum_{j \neq i}^{k} S_{ij} + \cdots + S_{i \cdots j \cdots k} \tag{3}$$

To solve the multi-objective optimization problem, the non-dominated sorting genetic algorithm II (NSGA-II) is applied to identify non-dominated design options. The population size is suggested to be twice the number of input variables, and up to 1800 evaluations are considered necessary to enable the convergence. The crossover and mutation probability are preset to 0.9 and 0.355 respectively referring to a statistical analysis of existing building optimization studies. However, these settings are subject to further adaptive variation to find the most suitable configuration. Non-dominated solutions of equal prevalence constitute the Pareto front after fitness functions reached the convergence. In order to obtain a single optimal solution, the weighted sum method is adopted with equal weightings for both lighting and cooling energy use to make the total energy demand the univariate optimization target.

3. Results and discussions

3.1. Initial sensitivity analysis results

Fig. 2 shows the preliminary SA result of 10 selected passive design factors for 5610 simulation runs. The left chart has eliminated any significant multicollinearity between different input variables. The filled rectangular cells with blue and lines from the left lower corner to the upper right corner indicate positive correlations between two corresponding inputs, while those filled with red and lines from the right lower corner to the left upper corner indicate negative correlations. The level of correlation can then be told from the color saturation of the rectangular cell and filled area of pie charts above the diagonal line. The right figure proved that WTR, WSH and IAMFC make no unique contribution to the variation of the total lighting and cooling demand.



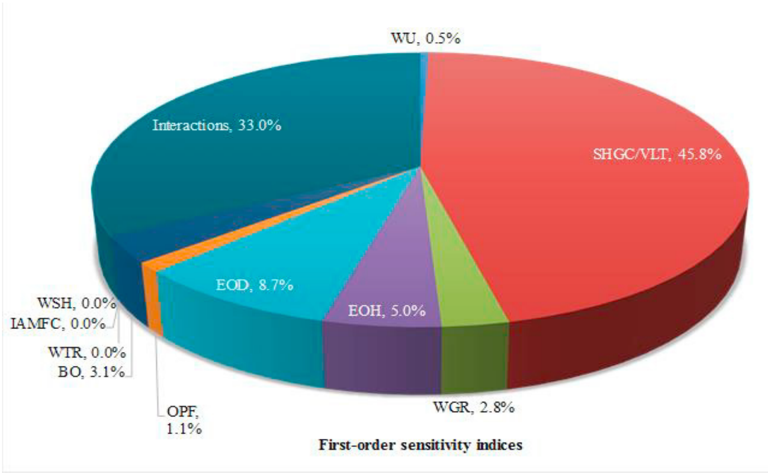


Fig. 2. Sensitivity analysis results

3.2. Preliminary optimization results

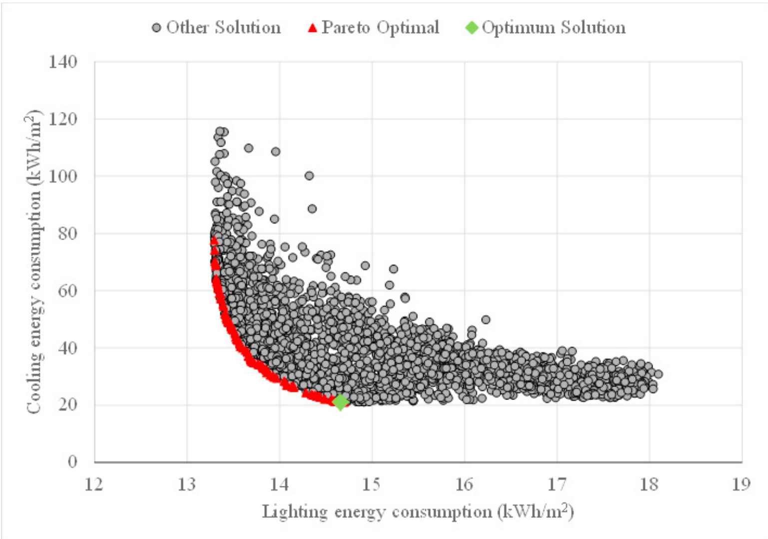


Fig. 3. Pareto frontier and optimum solution between the lighting and cooling energy demand

Totally 3124 evaluations were made before the optimization process achieved the convergence. 108 sets of Pareto optimal solutions were identified from the design problem space as highlighted in Fig. 3, where a trade-off conflict between the cooling energy and lighting energy demand was illustrated. The annual lighting load varied from 13.30kWh/m^2 to 14.70kWh/m^2, while the cooling demand changed from 21.04kWh/m^2 to 77.60kWh/m^2. As the Pareto optimization only imposed a partial order on solution candidates, the weighted sum method was then adopted to transform the bi-objective problem to a mono-objective one. The final optimum design achieved a low energy demand of 35.73kWh/m^2, which is attributed to a high window U-value and window to ground ratio of 5.81 and 0.49, a low window transmittance and wall thermal resistance of 0.11 and 0.26, as well as a small shading projection ratio of 0.15. All glazing of this design is facing north and less shaded by surroundings with an EOA of 14.00°.

4. Conclusions

A simulation-based design-optimization approach is applied to a passively designed generic building under the mixed-mode ventilation in hot and humid areas. Variance-based sensitivity analyses were conducted ahead of the optimization to reduce the search space of the evolutionary algorithm by removing insignificant factors. Conflicts between lighting and cooling objectives were attributed to the converse impacts stemmed from the window to ground ratio, overhang projection ratio and external obstructions. The ultimate optimal solution based on equally weighted objectives achieved a low energy demand level in Hong Kong. The findings from this paper can provide a potential design optimization procedure for passive designs in hot and humid area. The

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