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Simulation-based approach to optimize passively designed buildings: A case study on a typical architectural form in hot and humid climates

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ABSTRACT

Passive design strategies are important for achieving building sustainability given their proved influences over the building performance in both energy and indoor environmental aspects. The building layout, envelope thermophysics, building geometry and infiltration & air-tightness are major passive architectural parameters to improve the building energy efficiency. In this paper, a comprehensive literature review on simulation-based approaches to optimize passively designed buildings is conducted and corresponding research gaps are identified. Based on existing research methods, modelling experiments on a generic building are conducted to integrate robust variance-based sensitivity analyses with an early-stage design optimization process. Proposed mixed-mode ventilation and lighting dimming control algorithms are applied to the EnergyPlus model to simulate the total lighting and cooling energy demands by incorporating the related design criteria in a local green building assessment scheme. 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. Different settings of NSGA-II are also investigated to improve the computational efficiency without jeopardizing the optimization productivity. Furthermore, the sensitivity of optimum design solutions to external environmental parameters in hot and humid areas are explored. Findings from this study will guide decision-makers through a holistic optimization process to fulfill energy-saving targets in a passively designed green building.

1. Introduction

Building sectors account for approximately 60% of the total energy use in Hong Kong according to official statistics conducted by the local government [1]. Driven by the urge to reduce the building energy demand and minimize its environmental impacts, local building design codes (i.e. BEC 2015) and green building rating schemes (BEAM Plus Version 2.0) have been launched recently to enhance the sustainable development of local communities. Among multiple building design guidelines and assessment criteria, passive design is recently under the spotlight owing to its proved effectiveness on improving the cooling and lighting performance of buildings [2,3]. Because space cooling and lighting account for 41% of the total residential energy demand based on statistics of the Electrical and Mechanical Services Department (EMSD) (as shown in Fig. 1) [4], passive design features including the building layout, envelope thermophysics, building geometry and infiltration & air-tightness can make great contributions to low energy or near zero energy building designs [5]. Utilizing above passive strategies requires not only investigating their individual impacts as presented in some existing research [6–8], but also incorporating a holistic approach with deliberate consideration of interactive effects [9]. It is essential for architects and engineers to understand the relative importance of each strategy and deploy them appropriately at the first opportunity. Therefore, simulation-based optimization processes combined with in-depth and exhaustive sensitivity analyses (SA) are thoroughly reviewed in this study and an exemplary application of a proposed holistic design approach to a prototype high rise residential building in hot and humid areas will be analyzed and discussed in detail.

Abbreviation: AFN, airflow network; ANOVA, analysis of variance; BEAM, building environment assessment method; BO, building orientation; EMSD, electrical and mechanical services department; EOA, external obstruction angle; EOD, external obstruction distance; EOH, external obstruction height; FAST, Fourier amplitude sensitivity test; HVAC, heating ventilation and air conditioning; IAMFC, infiltration air mass flow coefficient; LHS, Latin hypercube sampling; NSGA-II, non-dominated sorting genetic algorithm II; OPF, overhang projection fraction; PRH, public rental housing; SA, sensitivity analysis; SHGC, solar heat gain coefficient; SRC, standardized regression coefficient; SRRC, standardized rank regression coefficient; VLT, visible light transmittance; WGR, window to ground ratio; WSH, wall specific heat; WTR, wall thermal resistance; WU, window U-values

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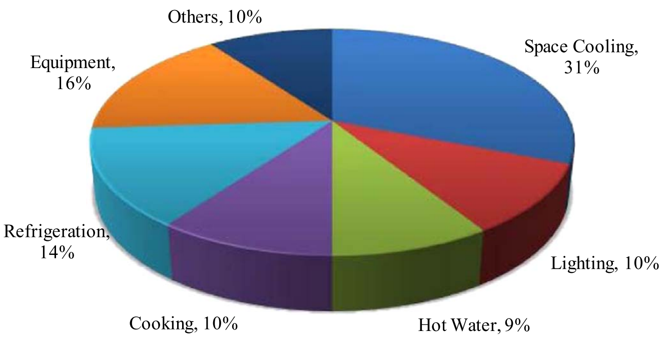

Fig. 1. Energy end use statistics of residential buildings in Hong Kong (by EMSD).

2. Review of simulation-based passive design approach

2.1. Sensitivity analyses to identify important design factors

Multiples building design factors can be subject to extensive and systematic examinations by different SA approaches using building simulation tools. According to Tian et al. [10], SA can be categorized as the local sensitivity analysis and global sensitivity analysis. The local SA is used to examine the impact of a certain input variable by independently changing its values while keeping other variables fixed [11]. A commercial building in Hong Kong was subject to the local SA with DOE-2 [12]. This study focused on the whole building design including the building structure, geometry, occupancy, load condition and HVAC system. Important input factors for the building annual energy use, peak load and load profile were identified respectively. A similar study was conducted to explore optimal energy-saving solutions for high-rise residential building in Netherland, where building envelope parameters such as the glazing type, window-to-wall ratio, sun shading and roof strategies contributed to a total energy saving of 42% [13]. Samuelson at al. performed a simple sensitivity analysis on the energy use intensity of case buildings in three urban contexts, where the window to wall ratio, glazing type and building orientation are determined to be the top three influential design factors [14]. Apart from investigating whole-building design inputs, passive design was specifically examined to decide their importance for five major climatic zones in China where retrofitting measures to improve the indoor thermal comfort and energy-saving performance for each zone were identified respectively [15]. The window opening size was also individually correlated with the peak load and annual energy consumption to provide concise design charts for early planning stages [16]. In addition, a few similar studies looked into the thermal load reduction efficiency by adjusting a single design variable such as the shape coefficient, envelope thermal resistance or occupant behavior pattern [17,18]. Instead of modulating one design factor at a time in building simulations, the global SA can study building performances with the regression (i.e. sampling-based), screening-based or variance-based methods [19,20]. The uncertainty and sensitivity of the indoor thermal comfort condition in a passively cooled office were examined by regression analyses [21]. According to the findings, the indoor weighted temperature excess hours (WTE) was most sensitive to the single-sided ventilation. Yildiz and Arsan estimated the impact of design parameters of low-rise apartment buildings in hot and humid climates using regression analyses coupled with the Latin Hypercube Sampling (LHS) and Monte Carlo approach [22], where the window size, U-value and solar heat gain coefficient (SHGC) were proved to have the greatest impact on heating and cooling loads of different floors. The Morris method (i.e. a popular screening-based method), which enables a qualitative assessment of the influence from each design variable, was integrated into a multi-criteria decision-making process for minimizing energy consumption and degree-hours of residential buildings in Brazil [23]. The most influential envelope feature in each climate zone was filtered out as further inputs to the performance evaluation of construction systems. The Analysis of Variance method (i.e. variance-based) was deployed in an uncertainty and sensitivity prediction of available solar irradiation on exterior building surfaces with shading devices [24]. The building latitude, orientation and width of overhang fins were proved to have more influence over calculated solar fractions and the uncertainty quantification process was identified as a crucial prerequisite for maintaining the building energy balance.

2.2. Optimization approach to improve building performance

Based on identified influential design variables from sensitivity analyses, a design optimization can be further conducted to improve the life-cycle cost effectiveness, energy efficiency and indoor environment qualities of buildings. Optimization studies can usually be classified to the mono-objective optimization and multi-objective optimization, where the latter is more common in building research area considering the requirements from multi-criteria design guidelines and assessment schemes [25–27]. Carlucci et al. carried out a four-objective optimization of a detached zero-carbon house in Italy and discussed trade-offs between the thermal and visual discomfort [28]. Futrell et al. performed both the pattern search and meta-heuristic optimization with GenOpt to simultaneously minimize the cooling, heating and lighting energy demand [29]. The target building was optimized respectively for each orientation and conflicts between thermal and daylight objectives were observed. In a similar work, energy performance optimization with the Multi-island Genetic Algorithm (GA) was performed on a software platform developed with the QT language and OpenGL interface [30]. When miscellaneous daylight illuminance indices were treated as optimization objectives, the window characteristics, building orientation and wall reflectance were thoroughly explored by evolutionary algorithms to search for an optimum interior design [31]. Final solutions were determined by their appearance frequencies in 6 sets of Pareto frontiers together with their mean distances to utopia points. As a holistic building design approach in early stages, multi-objective optimizations were also conducted with the energy use, thermal comfort and capital cost as objectives [32–34]. On top of abovementioned optimization objectives, Zhang et al. investigated trade-offs between the obtained solar radiation, space efficiency and shape coefficient of free-form buildings by changing building geometry inputs with Rhinoceros and Grasshopper [35]. In addition, the multi-objective particle swarm optimization (MOPSO) algorithm was exploited instead of GA methods to search for Pareto optimal solutions for a generic room model under different weather conditions of Iran [36]. Ruiz et al. proposed a methodology to accurately perform the automated building envelope calibration under the International Performance Measurement and Verification Protocol (IPMVP). A reliable energy simulation model was obtained from the Non-dominated Sorting Genetic Algorithm-II (NSGA-II). Furthermore, building orientations and window characteristics were optimized by comparing the performance of the Hooke-Jeeves Algorithm, Multi-objective Genetic Algorithm-II and Multi-objective Particle Swarm Optimization Algorithm in terms of the stability, robustness, validity, speed, coverage and locality [37].

According to the above brief introduction and in-depth literature review (summarized in Table 1), 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 demand minimization of a generic building model with selected significant input design variables based on a comprehensive sensitivity analysis. Simulation models with designed mix-mode ventilation and light dimming control strategies were coupled with NSGA-II to obtain the Pareto frontier as well as the final optimum solution under different algorithm settings and weather conditions. The originality of this