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# A multi-stage optimization of passively designed high-rise residential buildings in multiple building operation scenarios

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## HIGHLIGHTS

- A multi-stage design optimization approach is developed for passive building design.
- Multiple machine learning methods are applied to develop surrogate models.
- Computation efficiency of NSGA-II algorithm is greatly improved.
- Design optimization is applied to different ventilation and thermal load conditions.
- Applicability of passive design optimization in more diverse climate is studied.

## ARTICLE INFO

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## ABSTRACT

This article proposes a two-stage design optimization approach which is applied to a prototype passively designed high-rise residential building under different ventilation modes and thermal load requirements. Machine learning methods are employed to develop surrogate models for improving the computation efficiency of the multi-objective optimization process. The surrogate model is trained by modeling experiments with EnergyPlus and R, which can provide reliable energy performance indicators of generic building models featuring passive design parameters including the building layout, envelope thermophysics, building geometry and infiltration & air-tightness. The lighting, cooling and heating demands of the generic building model are determined by the hybrid ventilation and light diming control strategies in compliance with local green building assessment criteria in Hong Kong. The multiple linear regression (MLR), multivariate adaptive regression splines (MARS), and support vector machines (SVM) are examined by the statistical modelling. SVM is capable of fitting a surrogate model with the best prediction performance based on the coefficient of determination and root mean square error. In addition, both single-sided ventilation and cross-ventilation models under varied thermal load requirements are investigated to compare the preferable design solutions for each scenario. The multi-stage optimization approach is also applied to a Mediterranean climate to explore optimal design solutions in more diverse external environmental conditions. This research can provide a highly efficient design optimization tool to appropriately deploy passive architectural strategies in a green building project.

## 1. Introduction

Building energy consumption accounts for more than 60% of the domestic energy use in Hong Kong. This situation has raised the environmental awareness of the local government, academia and industry [1]. The Building Environmental Assessment Method (BEAM) has been practiced on both new and existing buildings in the last two decades to promote sustainability in the construction industry. Given the high energy demand, the local government has required all newly planned public rental housing (PRH) developments (typical high-rise residential buildings accommodating about 30% of the low-income population [2]) to comply with BEAM requirements. Among these green building requirements, passive design criteria are proposed in the current new construction guidelines to maximize their influences over the indoor environment performance and building energy demand [3,4]. As indicated by a comprehensive literature review, the building layout, envelope thermophysics, building geometry and infiltration & air-tightness are identified as key passive architectural design parameters. Their

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**Nomenclature**

*Abbreviation*

| | |
|---|---|
| AFN | airflow network |
| ANN | artificial neural network |
| 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 |
| GCV | generalized cross validation |
| HVAC | heating ventilation and air conditioning |
| IAMFC | infiltration air mass flow coefficient |
| LHS | Latin hypercube sampling |
| MARS | multivariate adaptive regression splines |
| MLR | multiple linear regression |
| NSGA-II | non-dominated sorting genetic algorithm II |
| OPF | overhang projection fraction |
| PRH | public rental housing |
| RMSE | root mean square error |
| SA | sensitivity analysis |
| SHGC | solar heat gain coefficient |
| SRC | standardized regression coefficient |
| SRRC | standardized rank regression coefficient |
| SVM | support vector machines |
| VLT | visible light transmittance |
| WGR | window to ground ratio |
| WSH | wall specific heat |
| WTR | wall thermal resistance |
| WU | window U-values |

impact on indoor environmental indices of the daylight, ventilation and thermal comfort has been validated by multiple sensitivity analyses [5–7], where the importance of selected passive design strategies is interpreted for decision-makers to prioritize resource allocation at the earliest opportunity. The sensitivity analysis was further coupled with multi-objective optimization to deliver the final building design in natural or mixed-mode ventilation conditions [8]. To further promote the applicability of this holistic optimization approach, the statistical modelling will be introduced to develop a surrogate model from robust modelling experiments and the new multi-stage method can conspicuously increase the computation speed of the design optimization process.

The statistical modelling usually applies regression analyses to derive a surrogate model (or meta-model) from the same training dataset that is used for sensitivity analyses. The dataset can be either generated from building operation records or simulations with well calibrated software [9,10]. Tian et al. applied a linear model and non-parametric model to predict the cooling and heating load of a group of campus buildings based on selected building geometry, envelope and internal heat gain inputs [11]. In this study, the meta-model was generated from simulation results with the Energy Performance Standard Calculation Toolkit. The linear model with a quadratic response transformation outperformed the more complicated MARS model [12]. The Gaussian Process Emulator and Polynomial Chaos Expansion were also used to obtain the meta-model from the building performance simulation. The model prediction accuracy under different quantities of training data and input variables was also investigated [13]. Using measured data in post-occupancy phase, a regression model for the energy consumption of a net-zero energy building was constructed and its prediction capability was compared to the whole building simulation with EnergyPlus and TRNSYS [14]. The regression model was based on two weather factors (i.e. the insolation level and dry-bulb temperature) from mixed-humid areas in U.S. Based on Brazilian regulations for residential buildings, surrogate models with limited choices of building envelope characteristics were developed to predict cooling/heating degree hours and energy consumption. The artificial neural network (ANN) was recommended over the multiple linear regression owing to its low prediction errors [15,16]. Apart from the above mentioned statistical modelling methods, the Support Vector Machines [17], Extreme Learning Machine [18,19], Poisson regression model [20], and Random Forest [21] were also applied to naturally ventilated or artificially conditioned buildings. They served as alternative prediction models for decision-making in the energy efficiency enhancement. Surrogate models developed from regression analyses can be then combined with an optimization algorithm to improve the computation speed. Xu et al. proposed a hybrid evolutionary algorithm with adaptive meta-models to enhance the convergence and speed performance [22]. In this new algorithm, previous populations in optimization were used to compose the surrogate model to replace the simulation software in the following fitness evaluation. The surrogate model had to be continuously updated every few generations. However, this adaptive meta-model approach was comparatively time-consuming when applied to a green building assessment, where all simulation settings apart from input parameters of interest are presumed to be constant for a certain building typology. A combined artificial neural network (ANN) and genetic algorithm approach was used to minimize the building energy use and life cycle impact. The approach focused on thermal and geometric features of windows and walls [23]. ANN was also applied in a cost-optimal building energy retrofitting, where a prediction model of the energy consumption and thermal comfort can help evaluate the global cost with a minimum computation time and acceptable reliability [24]. However, there is also argument on using such surrogate models to simplify the optimization process because of the accuracy and stability concern in a large input dimension [25].

From the above introduction and literature review, it can be clearly summarized that little existing research focuses on applying a surrogate model based multi-objective optimization to passively designed high-rise residential buildings in hot and humid climates. Most existing research on passive designs only explored limited design options and input distribution ranges. Furthermore, the influence of different ventilation modes and thermal load requirements on the optimized passive design configuration is seldom studied and discussed. To fill these research gaps, this paper proposed a multi-stage design optimization approach for a generic building model with selected passive design parameters and specified operation control algorithms. Both the simple linear and complicated non-parametric regression models are subject to comparative modelling experiments to develop robust surrogate models. These models are further coupled with a classic optimization algorithm to estimate optimal design configurations in miscellaneous ventilation modes, air-conditioning scenarios and weather profiles. The originality of this article lies in below aspects: (1) The optimization algorithm is incorporated with developed efficient surrogate models to tremendously reduce the computation effort of the design optimization process; (2) This research thoroughly explores the whole feasible range of passive design elements under different ventilation modes and thermal load requirements; (3) The multi-stage design optimization approach is highly integrated with the existing green building rating scheme, and the synergy of energy and indoor environment aspects are carefully considered in the decision making process; (4) The co-operation of heating and cooling was realized by imposing the lower and upper acceptability limits of ASHRAE 55 adaptive comfort standard on the indoor temperature control, where comfort performance no longer