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Developing a meta-model for sensitivity analyses and prediction of building performance for passively designed high-rise residential buildings ☆

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HIGHLIGHTS

- A meta-model for passively designed high-rise residential buildings is developed.
- An adequate sample size to acquire stable sensitivity estimations is determined.
- Rank transformations of model responses calibrated sensitivity coefficients.
- Window properties are determined to be most important input design factors.
- MARS models are closely fitted by predictors with acceptable prediction accuracy.

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ABSTRACT

This paper aims to develop a green building meta-model for a representative passively designed high-rise residential building in Hong Kong. Modelling experiments are conducted with EnergyPlus to explore a Monte Carlo regression approach, which intends to interpret the relationship between input parameters and output indices of a generic building model and provide reliable building performance predictions. Input parameters are selected from different passive design strategies including the building layout, envelop thermophysics, building geometry and infiltration & air-tightness, while output indices are corresponding indoor environmental indices of the daylight, natural ventilation and thermal comfort to fulfil current green building requirements. The variation of sampling size, application of response transformation and bootstrap method, as well as different statistical regression models are tested and validated through separate modelling datasets. A sampling size of 100 per regression coefficient is determined from the variation of sensitivity coefficients, coefficients of determination and prediction uncertainties. The rank transformation of responses can calibrate sensitivity coefficients of a non-linear model, by considering their variation obtained from sufficient bootstrapping replications. Furthermore, the acquired meta-model with MARS (Multivariate Adaptive Regression Splines) is proved to have better model fitting and predicting performances. This research can accurately identify important architectural design factors and make robust building performance predictions associated with the green building assessment. Sensitivity analysis results and obtained meta-models can improve the efficiency of future optimization studies by pruning the problem space and shorten the computation time.

1. Introduction

Green building rating schemes emerged in the 1960s as potential methods to improve the building sustainability from multiple aspects including the energy efficiency, material use, and indoor environment quality [1–4]. Given the fact that building sectors account for over 60% of total energy consumption in Hong Kong, BEAM (Building Environmental Assessment Method) has been practiced by researchers, designers and engineers for two decades to encourage the environmental awareness of the construction industry [5,6]. Especially, Hong Kong Housing Authority is taking a leading role to build BEAM certified high-rise residential buildings to accommodate nearly one third of the local population. In

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Nomenclature

Abbreviation

ACR	air change rate
ACT	ASHRAE55 comfort time
BEAM	building environment assessment method
BO	building orientation
ENP	effective number of parameters
EOA	external obstruction angle
GCV	generalized cross validation
HVAC	heating ventilation and air conditioning
IAMFC	infiltration air mass flow coefficient
IL	illuminance level
LHS	Latin hypercube sampling
MARS	multivariate adaptive regression splines
MSE	mean squared error
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
VIF	variance inflation factor
VLT	visible light transmittance
WGR	window to ground ratio
WSH	wall specific heat
WTR	wall thermal resistance

a recent update of this local green building rating scheme, passive design strategies are proposed to maximize their influences over the building sustainability from the earliest construction stage [7,8]. Passive designs covering the building layout, envelop thermophysics, building geometry and infiltration & air-tightness have been proved to significantly affect building performance in previous regression analyses [9–12]. These analyses can not only interpret the relative importance of each design strategy (i.e. the sensitivity analysis), but also predict future building performance (i.e. statistical modelling). Both the sensitivity analysis (SA) and statistical modelling can assist decision-makers in the initial stage of a construction project to efficiently deploy their resources over green building features.

1.1. Sensitivity analysis

The sensitivity analysis is widely applicable to relating input parameters with the overall building performance [13]. The unique contribution from each input can be determined by SA to prepare for future optimization of energy, environment and economic performances [14,15]. SA methods can usually be classified to the local SA where input parameters are varied one at a time and the global SA where all inputs are changed simultaneously [16–18]. The local SA is used to examine the energy performance of office buildings in Hong Kong with the DOE-2 program. Input factors of building loads, HVAC systems and refrigeration plants were varied separately to examine their influences over building energy consumption, the peak design load and annual load profiles. As a result, the lighting load, thermal setpoint and chiller coefficient of performance were proved to be most important design parameters in each category [17]. The optimum slab thickness of floors, ceilings and external walls was determined based on a local sensitivity analysis of the building envelop, where the maximum window to wall ratio was expressed by a function of the diurnal temperature amplitude [19]. 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 [20]. Apart from the above architectural features, shading effects from the balcony and surrounding structures were independently investigated by local SAs [21,22]. On the other side, the global SA is adopted to study the uncertainty and sensitivity of a passively cooled office building in moderate climates [23]. The impact of single-sided ventilation, passive stack and cross ventilation strategies on indoor thermal comfort conditions was investigated in this research, where the single-sided ventilation contributed to the largest uncertainty in the model output. In addition, design guidelines for conducting sensitivity studies on the total annual energy consumption of low-rise residential buildings are developed in a background of global warming [24,25]. The natural ventilation, window area, and solar heat gain coefficient are founded to be the most important design parameters in such buildings. However, the uncertainty of natural ventilation can be attributed to more elementary building designs such as window properties and opening configurations [26,27].

1.2. Statistical modelling

The statistical modelling is another application of regression analyses, in which meta-models (or surrogate models, emulators, etc.) are developed from either monitored building operation data or simulation cases from detailed engineering models [28]. Campus building stock data were used to construct statistical energy meta-model with both linear and non-parametric regression approaches [29]. In this study, linear models showed better prediction performances through a simple transformation of response data. Measured data of these buildings were also used to predict the base temperature and enthalpy with multiple linear regression analyses [30]. Hilliard et al. developed a predictive control strategy for a college building with the combination of EnergyPlus and R software. The deadband setpoint strategy performed better as a comfort maintenance measure compared to the fixed setpoint strategy in terms of energy reduction [31]. A Brazilian meta-model for both naturally and artificially ventilated residential buildings was developed from EnergyPlus simulations, where the artificial neural network model outperformed multiple regression models under a local energy labelling system [32]. In addition, Fan et al. proposed a data-mining method to develop an ensemble model for predicting the future energy consumption and peak demand [33]. The model was successfully applied to the tallest building in Hong Kong and was valuable for the fault detection and diagnosis as well as operation optimization.

According to the above introduction and literature review, it can be recognized that little existing research focuses on developing meta-models for passively designed high-rise residential buildings in hot and humid climates. Such studies should include a comprehensive statistical analysis on the model interpretation and prediction. This paper mainly focuses on the regression analysis of a generic building model with selected passive design parameters under a free-running mode. Miscellaneous internal loads and operational controls are excluded from the modelling process to observe the unique influence of the passive design on indoor environmental performances. Unlike most existing studies, the natural ventilation rate is treated as a model output to evaluate the impact of elementary architectural designs. The thermal comfort performance is another model output in the unconditioned building to represent the time when cooling energy consumption can be

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