Advanced Science and Technology Letters
Vol.89 (Architecture and Civil Engineering 2015), pp.89-93
http://dx.doi.org/10.14257/astl.2015.89.18

Stochastic Global Sensitivity Analysis for Retrofit Analysis in an Existing Building

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Abstract. Sensitivity analysis has been widely used for rational decision making of energy retrofit alternatives. A Sobol method is a variance based approach and provides powerful post-processing sensitivity results that enable to quantitatively identify influential and non-influential inputs. It can account for impacts of each input as well as impacts caused by all possible interactions between each input on building energy consumption. However, the Sobol method requires vast computation time. To overcome such computational disadvantage of the Sobol method, the authors employed a surrogate model using a Gaussian Process (GP) emulator. In other words, we combined the GP emulator and the Sobol method for energy retrofit decision making. In the paper, the following are addressed in detail: (1) global sensitivity analysis using the GP emulator, (2) decision making based on stochastic prediction.

Keywords: Sensitivity Analysis, Gaussian Process, Monte Carlo, Retrofit, Building Simulation

1 Introduction

Building Performance Simulation (BPS) tools predict dynamic behaviors of a given target building by assigning physical attributes to complex systems using verified mathematical equations. These BPS tools have been widely used not only to predict energy performance, but also to evaluate numerous design options [1]. To give the best scope to the aforementioned capacities, the BPS tools need to pick up true values among numerous simulation inputs. But, it is difficult to confirm each definite value due to uncertainty sources. To solve the uncertainty issues, Uncertainty Analysis (UA) can obtain predicted outputs having probability distributions and induce a stochastic decision-making throughout output variances in the BPS tools. With the stochastic results, a Sensitivity Analysis (SA) can be used to identify influential and non-influential inputs and to reduce output variances in a given range of the output space. In other words, the SA is a test of how uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model inputs [2]. The SA helps decision-makers focus on the important energy retrofit alternatives by

ISSN: 2287-1233 ASTL

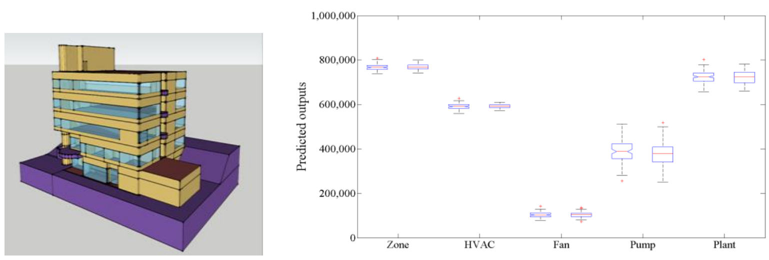
identifying efficient design options in line with the performance objective to below a given condition.

This paper addresses an energy retrofit analysis using the SA test of an existing office building. For this study, the calibrated EnergyPlus model was used. Please be noted that most BPS tools need to be calibrated and validated. And then the model was evaluated by the UA or SA test in order to achieve the optimal design solutions. These works are a high burden to retrofit experts under limited budget and time schedules. With this minds, we employed a Gaussian Process (GP) emulator which is a meta-model of the BPS tool. In other words, the GP emulator was coupled with a SA test to identify the optimal energy retrofit alternatives in all possible design space. For the SA test, we used a Sobol method that is a variance based approach.

2 Target building and simulation model

A 5-storey office building (floor area: 6,900 m^2) located in South Korea was selected as shown in Fig 1(a). The goal of this study is to simulate stochastic global sensitivity measures of the design variables with probabilistic characteristics using the validated EnergyPlus model after a calibration work, and then we require influential design options. For the calibration work, Bayesian calibration was used. Bayesian calibration estimates posterior distributions of unknown inputs in the Bayesian paradigm. Kim et al [3] reported the calibrated and validated results of the given target building (Fig. 1(a)) in detail. With the previous calibrated and validated EnergyPlus model, this study only focuses on the stochastic global sensitivity analysis. The 29 design variables with uniform probability distributions (continuous and discrete) were selected by collaboration of various decision makers (designers, engineers, retrofit experts, end users, and simulationists) and previous literatures [4-5].

The GP emulator, which is a non-parametric regression model, can quickly obtain accurate stochastic predicted outputs. In the GP emulator, a GP regression model with Gaussian noise using the given dataset represents a kernel matrix having zero mean function. And the GP regression model is expressed as a joint probability distribution, and it can obtain stochastic predicted outputs (mean and variance) of new input dataset according to the conditional probability. Fig 1(b) shows the difference of stochastic predicted outputs between EnergyPlus and GP emulator using the separate validated dataset. In the results, two samples have very similar distributions. It means that the outputs of the GP emulator are similar to those of EnergyPlus.



(a) EnergyPlus model (b) EnergyPlus vs. GP emulator

Fig. 1. Simulation model and comparison between EnergyPlus and the GP emulator

3 Sensitivity results

A Sobol method was used for the global sensitivity analysis of the given design variables [6]. However, Sobol method requires vast computation time (minimal number of sampling: N x ($2d$+2), where N is sampling size and d is the number of inputs) to derive significant sensitivity results. To deal with the problem, we performed coupling between the validated GP emulator and the Sobol method. As noted above, the GP emulator provides the mean values as well as the variances. With coupling between the GP emulator and the Sobol method, we can easily perform the stochastic global sensitivity analysis.

Table 1 only shows comparing between deterministic and stochastic results of fan out of thermal zone, HVAC, pump, fan, plant due to limited space. The stochastic global sensitivity analyses were resulted from 100 random samplings within 95% confidence intervals. In the results, the total order effects were greater than the first order effects due to interactions among the design variables, and a total of the first order effects were less than 1. Furthermore, ranks in order of influential design variables (for thermal zone, HVAC, pump, fan, plant) of the deterministic and stochastic results were identical except for the efficiency and pressure rise of the return fan. For deterministic global sensitivity analysis, the pressure rise of the return fan is more an influential design variable than the efficiency of the return fan. On the other hand, the stochastic result is a contrast to that. In other words, it can be inferred that the global sensitivity analysis was influenced by the discrepancy of the GP emulator. And the first and total order effects of the stochastic global sensitivity analysis should inform risks within 95% confidence intervals.

Table 1. SA results of the fan (Std. dev. : Standard deviation)

Unknown inputs	Deterministic		Stochastic							
	First order	Total order	First order				Total order			
			Mean	Std. dev.	2.5%	97.5%	Mean	Std. dev.	2.5%	97.5%
Efficiency of supply fan	0.406	0.412	0.407	0.001	0.404	0.409	0.410	0.002	0.406	0.415
Pressure rise of supply fan	0.404	0.408	0.402	0.003	0.395	0.409	0.406	0.002	0.401	0.410
Motor efficiency of supply fan	0.000	0.006	0.000	0.000	-0.001	0.001	0.002	0.003	-0.003	0.007
Efficiency of return fan	0.093	0.098	0.093	0.002	0.089	0.097	0.097	0.001	0.095	0.099
Pressure rise of return fan	0.093	0.098	0.092	0.003	0.085	0.098	0.096	0.001	0.093	0.098
Motor efficiency of return fan	0.000	0.006	0.000	0.000	-0.001	0.001	0.002	0.003	-0.003	0.007

Total	0.904	0.924	0.911	0.031	0.851	0.972	0.925	0.028	0.870	0.979

In case of the thermal zones, the lights and equipment were chosen as influential design variables. In terms of heating/cooling loads, the lights and equipment were more sensitive than the type and thickness of the insulation boards, the type and airtightness of the glasses, the number of occupants, and the indoor set-point temperatures. In case of the HVAC system, the design water inlet/outlet temperatures for cooling and heating were chosen as the influential design variables. Since HVAC system in the given building was CAV, the supply temperature is more sensitive than the supply flow rates. In case of the fans, the efficiency and pressure rise of the supply fans were chosen as the more influential design variables than those of the return fans. Since the supply fans had an additional pressure drop for heat exchange inside the air-conditioner (heating & cooling coils) and the air filter as well as the local resistance of the duct. In case of the pumps, the pump head ratio and the motor efficiency ratio of the condenser pump (primary pump) were chosen as more influential design variables than those of the chilled water and hot water pump (secondary pump). Finally, for the absorption chiller/heater of the plant, COPs for the cooling and heating were chosen as the influential design variables. And the COP for heating was selected as a more influential design variable than the COP for the cooling. To reach an efficient retrofit, it prefers to improve the heating efficiency.

4 Conclusions

In this study, a global sensitivity analysis was conducted for finding optimal design solutions among all possible design variables in the existing office building. For the retrofit analysis, the Sobol method, which can provide the sensitivity measures that enable to quantitatively identify influential and non-influential inputs, was chosen. As a result, stochastic global sensitivity analysis can be used for a post-processing method under uncertainty that considers the utilities of various decision-makers toward the risks. Furthermore, the sensitivity results should provide meaningful information to decision makers for objective and reliable retrofit analysis in an existing building.

Acknowledgement. This research was supported by a grant(11 AUDP G02) from Architecture & Urban Development Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

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