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Sensitivity analysis of building energy performance: A simulation-based approach using OFAT and variance-based sensitivity analysis methods

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A B S T R A C T

In this research, one-factor-at-a-time (OFAT) and variance-based sensitivity analysis methods integrate with EnergyPlus through MATLAB to define predominant variables affecting the energy efficiency of buildings in the early phase of building design. To explore the capabilities of the developed method, it is tested on a typical room model; and the impacts of the design variables, including building orientation, window size, overhang system, and the glazing and walls specifications on the building energy demands are studied in four main weather conditions of Iran. The local and global sensitivity analysis of the annual cooling, heating, lighting and total building electricity are carried out. The results show that for our typical case study, the window size is the prevailing parameter on the annual cooling, heating and total building energy electricity while the glazing visible transmittance has the greatest influence on the annual lighting one in all weather conditions. The developed simulation-based sensitivity analysis method demonstrates a useful tool that aids building energy engineers and decision-makers to concentrate on the most important parameters in the initial stages of planning and promote the building energy efficiency.

1. Introduction

Energy is one of the most important resources used by the modern society. Buildings account for a remarkable proportion of the total energy consumption in which the used energy and the carbon dioxide emission respectively comprises up to 40% and 36% in the world [1–5]. Accordingly, the energy efficiency of buildings has a great potential to decrease energy demands compared to other sectors such as transportation, industry, and agriculture.

Nowadays, improvement of buildings energy efficiency has become a major issue for building designers and engineers. One of the main obstacles to improve effectively the energy performance of buildings is the lack of engineering knowledge about the dominant parameters on the building energy consumption [6]. Thus, if the relative importance of design factors is well understood, it can be possible to obtain the optimum energy use of buildings through proper selection of design variables [6].

Sensitivity analysis of variables affecting the building energy demands is an important action for a further comprehension of energy conserving design principles and prioritizes energy efficiency measures [2,7]. In the early stages of the building design process, sensitivity analysis can give basic information about which input variables should be focused on in the next phases of the design as well as information about the variables with an ignorable influence on the energy use.

Nevertheless, the correct selection of the prevailing building variables is often difficult and requires good engineering knowledge of the model. During the past decades, application of the computer simulation programs such as DOE-2, EnergyPlus, ESP-r, and TRNSYS to handle complex engineering systems have emerged as a promising approach [7,8]. Thus, combining an appropriate sensitivity procedure with a building energy-modeling program provides an efficient and worthy tool to rank the design parameters based on their importance on the energy consumption in the shortest possible time.

2. Literature review

The techniques for sensitivity analysis employed in the field of building energy performance can be classified into local and global methods [7–10]. Local sensitivity analysis belongs to the class of the one-factor-at-a-time (OFAT) methods [7]. The OFAT method studies the behavior of model outputs with the changes in model inputs. According to this method, each time one design variable is changed over its entire

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range, while all other parameters are held fixed at their initial mode. This technique can be repeated with other variables [9–12]. It should be noted that OFAT method is often evaluated using gradients or partial derivatives of the output variables when the function of outputs is available [13]. Global sensitivity analysis methods evaluate output variations due to one input variable by varying entire parameters over their over their whole input space at the same time [14–17]. Thus, global methods assess the interaction of variables and provide robust sensitivity measures for the nonlinear models. The variance-based method is an appropriate sensitivity analysis method for complex nonlinear and non-additive models [7].

OFAT sensitivity analysis methods are straightforward to establish parameter dependency of the solutions, and useful to study problems with a few uncertain parameters. However, these methods only explores the variation of energy performance around a single point or a base case, and the interaction of other design parameters are not considered [7,10,13]. In addition, the fatal limitation of local sensitivity analysis methods is that they are unwarranted when the model input is uncertain or when the model is of unknown linearity [14,15]. In this respect, local sensitivity analysis methods give quite misleading results for nonlinear models. On the contrary, global sensitivity analysis approaches use a representative set of samples to explore the design space, which provides robust sensitivity measures in the presence of nonlinearity and interactions among the parameters compared to local sensitivity analysis methods. As a result, global methods are considered as more reliable and precise techniques for building analysis [7]. The main drawback of global sensitivity analysis methods is their higher computational costs than local methods as complexity and number of design parameters increase.

There are several methods of global sensitivity analysis in the building energy performance such as screening-based, Morris, variance-based, meta-model based and regression ones [7,9]. Among various global methods, variance-based sensitivity analysis methods have gained popularity [17]. Over the past years, simulation-based sensitivity analysis has been widely studied by many researchers. Tian [7] presented a review of the application of sensitivity analysis to provide the efficient recommendations on how effectively employ the sensitivity analysis in building performance. In another research, Tian et al. [1] employed regression analysis to know the relationship between input parameters and building energy performance. Nguyen and Reiter [8] carried out a comparison between the most-used sensitivity analysis methods in the building simulation using SimLab and EnergyPlus software. Sanchez et al. [2] proposed combining the implementation of ESP-r with Morris method and its extension for the analysis of interactions between the building design parameters. Yu et al. [6] carried out a sensitivity analysis of energy performance to evaluate the impacts of building parameters. Ruiz [18] integrated TRNSYS and MATLAB to recognize the most influential parameters affecting the energy consumption in office buildings. Furthermore, Tian and de Wilde [19] investigated the uncertainties and sensitivities in the prediction of the performance of buildings. De Wilde et al. [20] presented the application of two-dimensional Monte Carlo analysis to an office building. Capozzoli et al. [21] performed a sensitivity analysis using the ANOVA-FAST method. Moreover, Lam and Hui [22] examined the sensitivity of energy performance of office buildings to recognize important input parameters from points on the annual building energy consumption, peak design loads, and building load profiles. In a similar work, Tavares and Martins [23] conducted a sensitivity analysis of materials and equipment to evaluate the building energy consumption using the VisualDOE™ software. Recently, Sun [24] carried out a sensitivity analysis using TRNSYS platform to study the impacts of macro-parameter on the sizes of net zero energy building systems. Additionally, De Wit and Augenbroe [25] implemented uncertainty and sensitivity analysis with building energy simulation programs through Monte Carlo simulation technique. Burhenne et al. [26] analyzed the uncertainty associated with model factors of a building using a solar collector for heating and domestic hot water via Monte Carlo simulations. Besides, Dowd and Mourshed [27] investigated the sensitivity of building construction comprising multi-layered wall construction and changing sizes of glazing on energy use via dynamic thermal simulation. Basinska et al. [28] applied the global costs calculation method to do a sensitivity analysis for determining the optimum energy for residential buildings. Mainini et al. [29] estimated the sensitivity analysis of various locations, building orientation and window to wall ratio to appraise primary energy consumption for heating, lighting and cooling energy demands of office units. Wang et al. [30] investigated uncertainties in energy consumption using a simulation-based analysis of a medium-size office building. Daly et al. [31] examined the sensitivity of total predicted building energy use to hard-to-measure simulation inputs for two template Australian office buildings. Wang et al. [32] analyzed the influences of technical, economic and environmental parameters on the performances of building cooling, heating, and power system. Hemsath et al. [33] presented a method to compare the energy use of geometric variations and material considerations through the linear screening index and a Morris method. Rasouli et al. [34] used local sensitivity analysis to assess the impact of uncertainty of building and HVAC parameters using TRNSYS simulations. Hygh et al. [35] used EnergyPlus and a Monte Carlo framework to develop a multivariate linear regression model. Mauro et al. [36] used simulation-based uncertainty analysis to recognize the optimal representative building sample size, followed by simulation-based sensitivity analysis to recognize appropriate retrofit actions using EnergyPlus coupled with MATLAB. Mechri et al. [37] applied analysis of variance (ANOVA) method to specify the most impressible factors influencing building energy performance. Spitz et al. [38] employed the Sobol method to specify the influence of parameter uncertainty on an experimental house in France. de Wilde and Tian [39] used rank regression and multivariate adaptive regression splines methods to analyze the thermal performance of a theoretical office using SimLab and EnergyPlus. Eisenhower et al. [40] used a meta-model method for sensitivity analysis of a building model. Lam et al. [41] employed the analysis of variances (ANOVA) approach to analyze the effect of curtain wall parameters on the energy consumption. Shen and Tzempelikos [42] presented uncertainty and sensitivity analysis of day lighting and energy performance using the extended Fourier amplitude sensitivity-testing module in SimLab. Menberg et al. [43] investigated three different sensitivity approaches, including Morris method, linear regression analysis and variance-based method for a building test case using TRNSYS. Singh et al. [44] studied the uncertainty and sensitivity analysis of office buildings using EnergyPlus, Hyper Cubic Sampling and extended FAST methods. Aude et al. [45] presented a validation method for simulation codes describing thermal behavior of buildings using CA-SIS code and TRNSYS software and validated their code experimentally. Vartholomaios [46] presented a sensitivity analysis of urban form on the domestic heating and cooling energy consumption in a Mediterranean city using EnergyPlus and the standardized rank regression coefficients technique. de Lemos Martins et al. [47] proposed a fractional factorial DOE method coupled to a Simplified Radiosity Algorithm (SRA) to evaluate the irradiation availability on building envelopes while taking a large representative sample of contrasted urban block geometries into account. Peronato et al. [48] conducted a parametric design-based methodology to visualize building performance at neighborhood scale to convey the relative effectiveness of different design alternatives according to a wide range of building performance indicators. Yousefi et al. [49] performed a parametric study to investigate the influences of occupants' behavior on the efficiency of the building envelope including window and cladding materials in different climate zones using EnergyPlus. Hooshmand and Mahdian [50] carried out a local sensitivity analysis of effective parameters on the heating and cooling loads and on the energy consumption of a residential building using Carrier tool.

Despite the valuable investigations carried out in the field of

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