Energy and Buildings 68 (2014) 741–750

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Application of sensitivity analysis in building energy simulations: Combining first- and second-order elementary effects methods

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ARTICLE INFO

Keywords:
Energy demand
Buildings
Sensitivity analysis
Morris method
Elementary effects
Building thermal simulation

ABSTRACT

Sensitivity analysis plays an important role in the understanding of complex models. It helps to identify the influence of input parameters in relation to the outputs. It can also be a tool to understand the behavior of the model and can then facilitate its development stage. This study aims to analyze and illustrate the potential usefulness of combining first and second-order sensitivity analysis, applied to a building energy model (ESP-r). Through the example of an apartment building, a sensitivity analysis is performed using the method of elementary effects (also known as the Morris method), including an analysis of the interactions between the input parameters (second-order analysis). The usefulness of higher-order analysis is highlighted to support the results of the first-order analysis better. Several aspects are tackled to implement the multi-order sensitivity analysis efficiently: interval size of the variables, the management of non-linearity and the usefulness of various outputs.

1. Introduction

Energy consumption related to the building sector is recognized as a major part of the total energy consumption worldwide (37% of the final energy consumption in the EU in 2004) [1] and consequently a significant source of greenhouse gas emissions [2]. The growth in population, building services and comfort levels guarantees that this tendency will continue in the forthcoming years. Many tools have been developed to model the energy consumption in buildings (EnergyPlus, TRNSYS, ESP-r), particularly for end uses such as space heating and cooling, ventilation and lighting. In most cases, such models take into account coupling between phenomena (e.g. interactions between occupancy, micro-climate, envelope, HVAC, etc.) through coupling of different specialized sub-models and by using a large number of diverse input variables.

Sensitivity analysis can help in understanding the relative influence of input parameters on the output [3]. In the field of building energy models, combining sensitivity analysis and simulations tools can be useful as it helps to rank the input parameters (or family of parameters) and then to select the most appropriate to be considered, depending on the objective of the modeling. For example, this is particularly interesting when the modeling objective is related to the building design (e.g. sketch stage of the design, modeling retrofitting scenarios according to the only available input data) or when it is to define archetypes. Another application is in the development stage of the tools, and more precisely the definition of possible simplification of models or in the validation of assumptions in the selection of input parameters that must be considered. In these cases, and depending on the objectives of the tool developed, some sub-models and their corresponding input data may become secondary. A solution consists of using a detailed model in the upstream stage, combined with a sensitivity analysis in order to rank the set of parameters and identify the coupling between them. Then, the selection of the most important variable helps to define the structure of the simplified model.

In this study, we propose combining the implementation of ESP-r [4] with two sensitivity analysis techniques: the Morris method [5] and an extension of this methodology for the analysis of interactions between the parameters [6]. In Section 2, sensitivity analysis methods are quickly reviewed. Then, the elementary effects method and its second-order variant are described, together with the apartment building test case (Section 3). Finally, results are presented and discussed for the two methods used (Section 4).

2. Background

2.1. Sensitivity analysis: current approaches

Sensitivity analysis methods have been studied by many authors in the past decades as they have demonstrated their strength in many sectors. Throughout this period new methods and improvements have been developed, offering different solutions depending

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http://dx.doi.org/10.1016/j.enbuild.2012.08.048

on the objective. Hamby [7] proposed an inventory of techniques for parameter sensitivity analysis which he divided into three different categories:

- Sensitivity analysis methods assessing the influence of individual parameters. These include *Differential Sensitivity Analysis, One-at-a time sensitivity measures, Factorial Design, Sensitivity Index, Importance Factors, and Subjective Sensitivity Analysis.*
- Parameter sensitivity analysis utilizing random sampling methods (simple random sampling, Monte Carlo, Latin Hypercube). In this group are listed the methods: *Scatter plots, Importance Index, 'Relative Deviation', 'Relative Deviation Ratio', Pearson's r, Rank Transformation, Spearman's ρ, Partial Correlation Coefficient, Regression, and Standardized Regression techniques.*
- Sensitivity tests involving segmented input distributions: *the Smirnov test, the Cramer Von-Mises test, the Mann–Whitney test, and the squared-ranked test.*

The author then applied these different methods to a case study related to the nuclear industry, in order to compare them in terms of reliability, computational requirements and ease of implementation [8]. The study identified the One-at-a time method as being the simplest but pointed out that it becomes time-intensive with large numbers of parameters. Saltelli et al. [9] also describe the different sensitivity analysis techniques. For these authors, techniques can be divided between global and local methods. Local methods are commonly based on the estimation of partial derivatives in order to obtain a qualitative analysis of the importance of each factor on the output response for a limited subset and particular values of the input variables. Global methods vary all the parameters and try to obtain information for a subset of input variables in a wider domain. Global methods can also be divided into quantitative and qualitative techniques. Santner et al. [10] developed the parallel between the physical experiments and the concept of computational experiments as it is understood in this study. In particular, these authors described the added value of sensitivity analysis in such an experiment. This was taken up by Saltelli et al. [9] who presented the One-at-a time sampling for sensitivity analysis for multiple parameters.

2.2. Principles of the elementary effects method

The Morris method is derived from One-factor-at-a-time (OAT) screening methods to identify the subset of the main important input factors among a large number of k input parameters in a model. This method characterizes the sensitivity of a model with respect to its input variables through the concept of *elementary effects*, which are approximations of the first order partial derivatives of the model [5]. These elementary effects are estimated at various sampled points, randomly selected on a p-values regular grid, defining a relevant design of computational experiments. The average and standard deviations of elementary effects enable negligible and influencing variables to be sorted and linear and non-linear influences to be distinguished. In some respect, this method can be considered intermediate between a local sensitivity analysis and global quantitative methods described above. It is a general approach (model-independent), which achieves a good compromise between accuracy and efficiency. Applications can be found in a number of fields including Environmental Modeling and Agriculture [11], Biophysics [12] and Nuclear Engineering [13]. However, in spite of its advantages, its applications still remain limited.

Other methods, such as variance-based sensitivity indices (VBM), have been proposed [14]. Although they generally provide better information to distinguish non-linearities and interactions [15], the computational cost is much higher: a variance-based analysis for a 12-input parameter model requires at least 14,000 runs of the model, about one hundred times the cost of a first-order Morris analysis (and still ten times more than a second-order Morris analysis).

2.3. Experience with the elementary effects methods for building thermal simulation

Some studies have tested the advantages of the Morris method applied to building energy simulations. Breesch and Janssens [16] implemented it to identify the most important parameters that cause uncertainty in the predicted performances of natural night ventilation. They used a two-zone model in the thermal simulation tool TRNSYS coupled with an infiltration model COMIS. This analysis revealed that the internal heat gains, local outdoor temperature and the diurnal internal convective heat transfer coefficient were the parameters with the greatest impact on thermal comfort. Brohus et al. [17] applied the methodology to reduce a set of 75 parameters used to obtain an accurate output energy consumption distribution. The Morris method was also used as a first indication of correlation or non-linear effects between the parameters. Finally, this method was compared with the Fourier Amplitude Sensitivity Testing method (FAST). The results of both analysis helped in evaluating a safety factor for the annual energy consumption at the design level. De Witt [18] compared the Morris method with the sequential bifurcation technique using a mono-zone office of 81 parameters as a model. Both techniques found the same set of important parameters (12) which explained 94% of the variability of the model output defined as the number of hours of overheating. Corrado and Mechri [19] analyzed the heating and cooling needs of a two-storey single-family house in Turin with the Morris method to calculate the uncertainties in energy rating. The sensitivity analysis showed that only 5 of 129 factors were responsible for most of these uncertainties: the indoor temperature, the air change rate, the number of occupants, the metabolism rate and the equipment heat gains. Heiselberg et al. [20] identified the most important design parameters in relation to a building's performance with a focus on the optimization of sustainable buildings. They found that the mechanical ventilation rate in winter and lighting control were the most influential parameters in an office building of 7 floors.

The extension of the Morris method for second- and upper-order analysis has still not been applied in the area of building energy simulations despite its advantages stated in other analysis and its low computational cost compared to more sophisticated techniques like variance-based and FAST methods.

3. Methodology

3.1. The elementary effects method

The building thermal model can be represented by a function $y(x)$ where y is the output variable of interest (scalar) and x is a vector of real input variables with k coordinates, each input variable being defined within the range of a continuous interval. Input variables are transformed into reduced dimensionless variables in the interval (0;1) as $x'_i = (x_i - x_{\min}/x_{\max} - x_{\min})$.

$x_{\min}$ and $x_{\max}$ are the minimum and maximum of the input variable x_i, respectively. The domain of the vector x is then a hypercube H^k with unit length, a subset of $\mathbb{R}^k$. For each reduced input variable, only discretized values are considered, using a p_i values regular grid (with step $(1/p_i - 1)$): 0, $(1/p_i - 1)$, $(2/p_i - 1)$, . . ., 1. Although a single grid value is generally used for all the variables, it is possible to use a specific one for each input variable x_i. This enables qualitative input variables with two levels to be incorporated, represented in the Morris design by a 2-value grid, while keeping a more precise grid for continuous input variables.