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Application of sensitivity analysis in design of sustainable buildings

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ABSTRACT

Building performance can be expressed by different indicators such as primary energy use, environmental load and/or the indoor environmental quality and a building performance simulation can provide the decision maker with a quantitative measure of the extent to which an integrated design solution satisfies the design objectives and criteria. In the design of sustainable buildings, it is beneficial to identify the most important design parameters in order to more efficiently develop alternative design solutions or reach optimized design solutions. Sensitivity analyses make it possible to identify the most important parameters in relation to building performance and to focus design and optimization of sustainable buildings on these fewer, but most important parameters. The sensitivity analyses will typically be performed at a reasonably early stage of the building design process, where it is still possible to influence the most important design parameters. A methodology of sensitivity analysis is presented and an application example is given for design of an office building in Denmark.

1. Introduction

Energy use for room heating, cooling and ventilation accounts for more than one-third of the total, primary energy demand in the industrialized countries, and is in this way a major polluter of the environment. To successfully achieve the targets set out in the Kyoto protocol it is necessary to identify innovative energy technologies and solutions for the medium and long term which facilitates the implementation and integration of low carbon technologies, such as renewable energy devices, within the built environment. Building performance can be expressed by different indicators as primary energy use, environmental load and/or the indoor environmental quality and a building performance simulation can provide the decision maker with a quantitative measure of the extent to which an integrated design solution satisfies the design objectives and criteria.

In Denmark new requirements for primary energy consumption in new buildings, including heating, cooling, domestic hot water, ventilation and lighting (not included for residential buildings), entered into force in April 2006. The total primary energy use has to be calculated by a newly developed software program BE06 [11], which applies a simplified method for calculation of energy use based on mean monthly average values for climate data, heat loads and occupation schedules.

The primary energy consumption for all buildings (except residences) must not exceed:

$$\left(95 + \frac{2200}{A}\right)\ \text{kW h/m}^2\ \text{year}$$

where A is the heated floor area of the building.

In order to reach a label as a low energy building the primary energy consumption must not exceed:

$$\text{Class 1}: \quad \left(35 + \frac{1100}{A}\right)\ \text{kW h/m}^2\ \text{year}$$

$$\text{Class 2}: \quad \left(50 + \frac{1600}{A}\right)\ \text{kW h/m}^2\ \text{year}$$

In the calculation of the primary energy use, energy use for heating is multiplied by a factor of 1.0 while electricity use is multiplied by a factor of 2.5. Besides requirements on the energy consumption the building regulations also put requirements on air tightness (1.5 l/s m^2 floor area at a pressure difference of 50 Pa) and heat loss (6 W/m^2 envelope (except windows and doors) at a temperature difference of 32 K). The latter means that the average U-value for the building envelope must not exceed 0.19 W/m^2 K.

The new requirements implied a reduction of 25–30% from the previous requirements and the plans for the future development include similar reductions in 2010 to a maximum level similar to Class 2 and in 2015 to a maximum level similar to Class 1. Achievement of reductions of the energy use in new buildings to low energy class 1 or 2 will require development of more holistic

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building concepts, where an integrated design approach is needed to ensure a system optimization and to enable the designer(s) to control the many design parameters that must be considered and integrated.

Therefore, in the design of integrated building concepts it will be very beneficial to be able to identify the most important design parameters in order to more efficiently develop alternative design proposals and/or reach optimized design solutions. This can be achieved by applying sensitivity analysis early in the design process.

A sensitivity analysis makes it possible to identify the most important design parameters in relation to building performance and to focus design and optimization of sustainable buildings on these fewer, but most important parameters. A sensitivity analysis will typically be performed at a reasonably early stage of the building design process, where it is still possible to influence the selection of important parameters. The objective of the present paper is to present a methodology of sensitivity analysis and by an application example of the design of an office building in Denmark to demonstrate the benefits achieved in a design process and an example of what design parameters contribute significantly to sustainable building energy performance in office buildings in Denmark.

2. Sensitivity analysis

A sensitivity analysis determines the contribution of the individual design variable to the total performance of the design solution. It can be used to ascertain which subset of design variables accounts for the most of the building performance variance (and in what percentage). Those design variables with a small percentage can be given any value within their range of variability and will results in simplification of the design task. Sensitivity analysis can be grouped into three classes: screening methods, local sensitivity methods and global sensitivity methods.

Screening methods are used for complex situations which are computational expensive to evaluate and/or have a large number of design parameters as in sustainable building design. It is an economical method that can identify and rank qualitatively the design parameters that control most of the output variability, i.e. energy performance. The methods are so-called OAT-methods (one-parameter-at-a-time) in which the impact of changing the values of each design parameter is evaluated in turn (partial analysis). A performance estimation using “standard values” is used as control. For each design parameter, usually two extreme values are selected on both sides of the standard value. The differences between the result obtained by using the standard value and using the extreme values are compared to evaluate which design parameters the building energy performance is significantly sensitive to.

Local sensitivity methods are also often based on an OAT approach, where evaluation of output variability is based on the variation of one design parameter, while all other design parameters are held constant. This method is useful for comparison of the relative importance of various design parameters. The input–output relationship is assumed to be linear and the correlation between design parameters is not taken into account.

Global sensitivity methods are approaches where output variability due to one design parameter is evaluated by varying all other design parameters as well, and where the effect of range and shape of their probability density function is incorporated. An array of randomly selected design parameter values and calculated output values provides a means for determining the design parameter sensitivity. The influence of other design parameters is relevant to consider in sensitivity analysis since the overall building performance is of importance. Distribution effects are meaningful because design parameter sensitivity depends not only on the range and distribution of an individual design parameter, but also on other parameters to which the performance is sensitive. Design parameter sensitivity is often dependent on the interactions and influences of all design parameters.

The basic six steps in a sensitivity analysis include:

1. Identification of questions to be answered by the analysis, define output variable(s), define an appropriate model and its design parameters.
2. Determine design parameters to be included in an initial screening analysis. Perform the screening analysis and select the most important design parameters for further analysis.
3. Assign probability density functions to each selected design parameter.
4. Generate an input vector/matrix (maybe considering correlation) through the use of an appropriate random sampling method.
5. Calculate an output distribution based on the generated input matrix.
6. Assess the influence and relative importance of each design parameter on the output variable(s).

A number of different mathematical methods for sensitivity analysis can be found in the literature [1–6]. Based on the available information the Morris method [6] is evaluated as the most interesting for sensitivity analysis in sustainable building design as

- The method is able to handle a large number of parameters.
- It is economical – the number of simulations are few compared to the number of parameters.
- It is not dependent on assumptions regarding linearity and/or correlations between parameter and model output.
- Parameters are varied globally within the limits.
- Results are easily interpreted and visualised graphically.
- Indicates if parameter variation is non-linear or mutually correlated.

Sensitivity analyses can in principle be used for all kinds of projects, however, the more spread found in the various design parameters and the higher the sensitivity to those parameters, the more benefit will be gained from the analyses. The sensitivity analyses will typically be performed by consulting engineers preferably at a reasonably early stage of the building design process, where it is still possible to influence the important parameters. The sensitivity analysis makes it possible to identify the most important design parameters for building performance and to focus the building design and optimization on these fewer parameters. The main barrier for application of sensitivity analysis in building performance assessment is the increase in calculation time and complexity. Even if the Morris method is relatively effective about 500 calculations of output variables are needed for an investigation of 50 variable design parameters.

3. Description of method

3.1. Identification of problem and selection of calculation method

The first step in a sensitivity analysis is to identify the question(s) to be answered by the analysis, i.e. define the output variable. Often the analyses will focus on the building energy performance (e.g. kW h/(m^2 year)) and/or the indoor environmental quality (e.g. average/cumulated predicted percentage of dissatisfied (PPD) or the number of hours during a year a certain