The influence of design uncertainties in annual energy consumption

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The aim of this research is to provide a conceptual framework to investigate the impact of uncertainties in evaluating the performance of a building early in the conceptual design phase. The research question addressed was how the annual energy consumption of a building was affected quantitatively by simple design configurations. A local sensitivity analysis was performed by changing three input parameters, WWR (window to wall ratio), R-value (thermal resistance) for mass exterior wall, U-value (thermal transmittance) for mass glazing, to identify which parameter has more impacts on building performance. Preliminary results indicated that whole building energy consumption is affected more by the WWR parameter. The paper is concluded with a case study of a real-world construction project that demonstrates the utility of sensitivity analysis for the decision-making process.

Keywords: Uncertainties, early design phase, conceptual mass, annual energy consumption

1 Introduction

The building sector is responsible for a large share of human environmental impacts. The relationship between energy, construction industry, and the environment has become more significant when the data show that the construction sector in Europe consumes relatively 40% of the total consumed energy.

Architects, designers, and planners are the key players for reducing the environmental impacts of buildings, as they define them to a large extent. The design phase, as the most critical step where important decisions are made, should be considered for achieving these goals by evaluating buildings from an environmental perspective.

In the earliest design phase, there are numerous uncertainties due to the lack of information on materials and processes. Designers, therefore, cannot quantify precisely the environmental impacts of buildings in their designs early on. For this reason, it is necessary to introduce a method which can evaluate the design uncertainties in the earliest phases and give accountable feedback on how the design aspects influence the whole building performance in terms of annual energy consumption.

Hopfe et al. described uncertainties in design parameters as design variations that occur during the planning process. They can be either caused due to a lack of knowledge of the designer or they arise due to changes or irregularities in the planning phase of the building. The consideration of design uncertainties could, therefore, improve and enable design decision support, in particular, if it would be augmented by sensitivity analysis (Hopfe *et al.*, 2007).

For our research study, a local sensitivity analysis (differential sensitivity analysis) is utilized and a general workflow (figure 2) is proposed to evaluate the most influenced parameter in total energy consumption.

Figure 1: Ferdinand Tausendpfund GmbH & Co. KG office building, in Regensburg, Germany built in 2017.

Figure 1 shows Ferdinand Tausendpfund GmbH & Co. KG office building that is used for our case study during this research. It has three stories and is 27m long, 14.7m wide, and 9.8m tall.

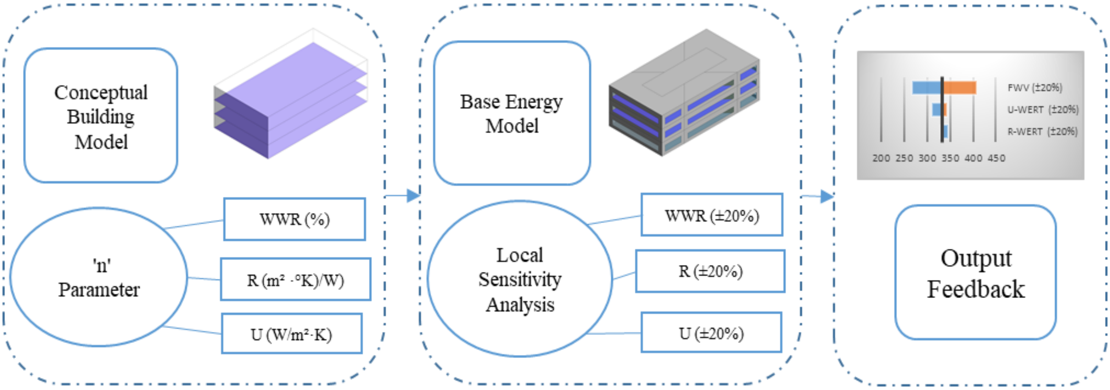

Figure 2. The general workflow for the analysis

This study considers the utilization of Autodesk Revit for building modelling purposes, the Green Building Studio energy simulation interface for developing the geometric model of the building and DOE2 as a simulation energy engine. In the earliest design phase (the conceptual massing elements “phase”), the energy analysis can be run on Green Building Studio in the cloud and provide analysis results directly within the tool (E.Kamel & A.M.Memari, 2018).

Based on the case study building, a parametric BIM model is modelled and for different input parameters, a range of ±20% uncertainty is given. Then, energy simulation analysis is conducted to evaluate the relation between energy performance and key design parameters under consideration. In early design phases, energy simulation is useful for comparative analysis of multiple design schemes. Besides, energy simulation tools can facilitate a broader search of the design space by allowing the parametric analysis of a whole building or a single room, floor, or façade (J.S.Hygh *et al.*,2012).

2 Background and related work

Y.Ibraheem et al. presented in their research a set of 6 variables categorized in system and subsystem variable and a 'measure level' of each variable were also specified. Sub-system variables were clustered into sub-groups. Those are the depth of panels, d/l (d=depth of the PVSD and l=distance between the PVSDs), angle of inclination and glazing systems. Then, the trend of the mean electricity consumption was estimated (Y.Ibraheem *et al.*,2018).

P. Heiselberg et al. considered a set of 21 design parameters and for each parameter, the range and distribution are defined. For some design parameters, the probability density function is given as a normal distribution defined by its mean value and the standard deviation. For other design parameters, a uniform distribution is defined by four discrete values. Then a sensitivity analysis was performed to identify the important design parameters to change to reduce the energy use in the reference building (P. Heiselberg *et al.*,2007).

S. Yang *et al.* presumed a set of 11 parameters where their ranges are considered based on the Chinese Design Standard for Energy Efficiency in public buildings (GB 50189). The GB 50189-2005 specified the requirements for these technical parameters in all climate zones of China. Then a comparison between different methods for sensitivity analysis is provided (S. Yang *et al.*,2016).

In the above research studies, the range and the distributions for each parameter are defined based on domain knowledge and numerous studies on the required information for energy performance simulation. Since these parameters taken into account obtain different ranges of variation of the building with their measurement units and values, it is laborious to identify with a precise quantification which input parameter influences the output performance. The vague determination of the parameter range accompanied by non-coherent different ranges of the parameter when they are compared with each other can cause evasive overview on how uncertainties influence in the output results.

3 Methodolgy

The proposed method in this research is the local sensitivity analysis which belongs to the class of the one-factor-at-a-time methods. This method (also called Differential Sensitivity Analysis) usually calculates the sensitivity of parameters when one input is changed and all others are fixed.

The DSA method requires a base case simulation in which input parameters are set for initial evaluation of the output performance. Then the simulation is repeated with one input parameter changed from P to P±δP and the effect on the output parameters of interests is noted. This is done for each parameter, giving a total of N+1 simulations for analysing the effects of N uncertain parameters (Iain Macdonald & Paul Strachan, 2001).

The output result (OP) can be expressed in general by the multivariable function f with n numbers of depending variables (input parameters):

$$OP = f\,(x_1, x_2, \ldots, x_n) \qquad (1)$$

By using the chain rule of partial differentiation, its differential is given by:

$$df = \frac{\partial f}{\partial x_1} dx_1 + \frac{\partial f}{\partial x_2} dx_2 + \cdots + \frac{\partial f}{\partial x_n} dx_n \tag{2}$$

The gradient of the function for parameter x_1, can be expressed as:

$$\frac{df}{dx_1} = \frac{\partial f}{\partial x_1} + \frac{\partial f}{\partial x_2}\frac{dx_2}{dx_1} + \frac{\partial f}{\partial x_3}\frac{dx_3}{dx_1} + \cdots + \frac{\partial f}{\partial x_n}\frac{dx_n}{dx_1} \tag{3}$$

We assume that input parameters are independent from each other and if x_1 is independent of x_2, x_3, …, x_n, then:

$$\frac{dx_2}{dx_1} = \frac{dx_3}{dx_1} = \cdots = \frac{dx_n}{dx_1} = 0 \tag{4}$$

$$\frac{df}{dx_1} = \frac{\partial f}{\partial x_1} \tag{5}$$

Equality of the above equation holds as long as the difference from the base case value is not very large (Lam, J. C., & Hui, S. C., 1996).

The first step in sensitivity analysis is to determine the range and the probability distributions of the inputs. The ranges (or distributions) of inputs are mainly dependent on the research purposes for sensitivity analysis (Wei Tian, 2013).

When a sensitivity analysis considers only the variation of the output performance in different design options caused by the uncertainties of the inputs, it is recommended to take the input variables as discrete or continuous uniform distributions. For our case study, a discrete uniform distribution is implemented for each of the input parameters. In the design phase, the variation of the inputs is equally likely to happen with the same probability in all their range and through this assumption, it is accurately introduced an evaluation of the influence of the inputs in various design options.

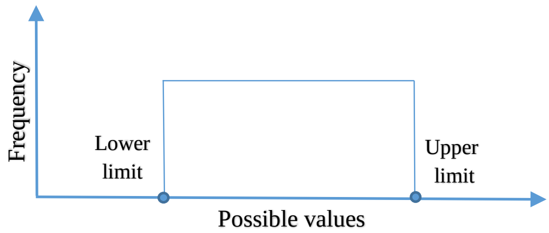

Figure 3. Modeling ranges with uniform distribution functions for each parameter

Then sensitivity analysis is used to decide whether a different value of the input is necessary compared to other measures. When a sensitivity analysis considers the evaluation of the output performance in an existing building or tries to perform a retrofit analysis based on different use of materials (inputs), it is recommended to presume normal distributions of the inputs. This is because natural variations of a building life cycle include the change in the conditions of buildings during their construction, operation and maintenance phase and their depreciation.

4 Case study

For the "conceptual mass" phase, where this research is focused on, a 3D-solid object (figure 4) is modelled in Revit based on the real case study mentioned above. It has three stories and is 27m long, 14.7m wide, and 9.8m tall (figure 1).

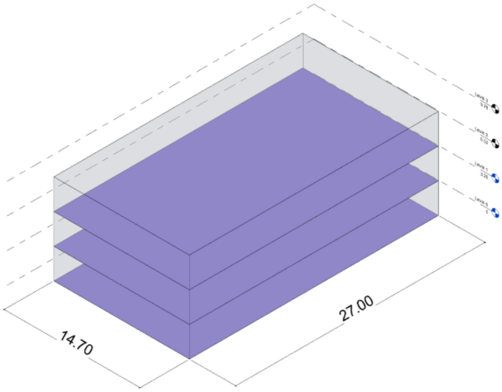

Figure 4. Conceptual 3D-model of Ferdinand Tausendpfund GmbH & Co. KG office building

This study takes into account three different input parameters a) WWR (%), b) R ($m^2 \cdot °K$)/W), c) U($W/m^2 \cdot K$), where WWR represent window to wall ratio, R-value is the thermal resistance for mass exterior wall and U-value is a measure of thermal transmittance for mass glazing (Table 1).

Table 1. The 3 design parameters and associated sampling ranges used in the sensitivity analysis*

Input parameters	**Base case**	**Range**	
Window-Wall Ratio (%)	45	45 (-20%)	45 (+20%)
Exterior Walls (R-value-(m^2 • °K)/W)	1.91	1.91(-20%)	1.91(+20%)
Exterior Windows (U-value-W/m^2•K)	3.17	3.17(-20%)	3.17(+20%)

* For discrete parameters, each number represents a codified name of building components in Revit (e.g. 1.91 means "High Mass Construction - Typical Mild Climate")

It is assumed a building operational schedule of 12 hours / 5 days and the "Central VAV, Electric Resistance Heat, Chiller 5.96 COP" type for the HVAC system. An initially base study with fixed parameters and then 2 other cases for each of three input parameters with a variation of ±20% is analyzed.

For the base study and for each study where the parameters have the above-mentioned variation, a whole building energy simulation is conducted (figure 5).

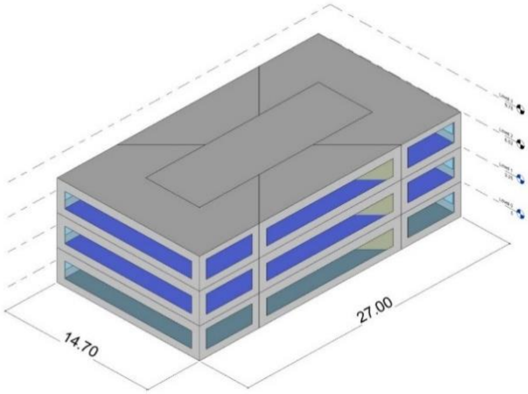

Figure 5. Energy model of the conceptual 3D-model.

This analysis and the sensitivity measures are calculated when one factor is changed in its maximal variation (+20% and -20%) and the other factors are maintained fixed. This study analysis a set of 7 samples, 1 sample for the base case and 6 samples for the cases where the uncertainty of ±20% is given. Figure 6 presents the variation from the base case of the annual energy consumption results based on the given uncertainty.

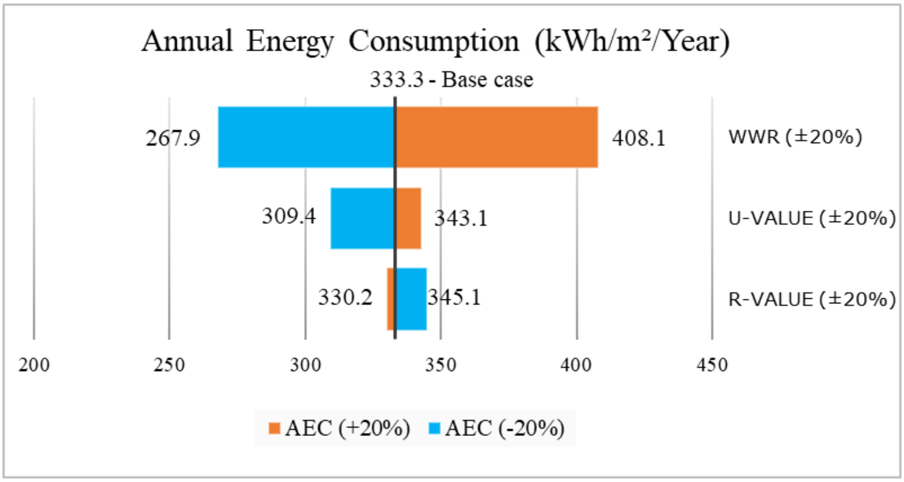

Figure 6. Comparison of the uncertainty in annual energy consumption results for three different parameters, a) WWR, b) Uvalue, c) Rvalue

As it is shown in figure 6, the vertical line presents the value of annual energy consumption for the base case, the orange part of the graph presents variation of the values when the uncertainty of (+20%) is given for each parameter and the light blue part of the graph refers the variation of the values when an uncertainty of (-20%) is given. The total variation of energy consumption for the three parameters are Δ_{WWR}=140.2 kWh/m^2, Δ_{Uval}=33.7 kWh/m^2 and $\Delta_{R\text{-}val}$=14.9 kWh/m^2. It is concluded that WWR parameter has the biggest influence in the output range compared with two other parameters.

5 Conclusions

This study has evaluated the influence of design uncertainties in the annual energy consumption of a three-story building early in the "conceptual mass" phase. The local sensitivity analysis is adaptable for this study regarding the limited design information that the designers might have in the first designing steps of a building. An overview of the impact that a ±20% uncertainty given to the input parameters have in energy consumption variation is presented and this result can help the designer when considering different design aspects and type of materials. This approach might lead to more precise energy calculation in the early design phases where the uncertainty given for WWR parameter results as the highest impact factor in energy consumption. The main limitation of the proposed method is that it does not support taking the interactions between the different parameters into account, but in further studies when a more detailed design is considered, it would be valuable to follow a general approach, such as global sensitivity analysis.

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