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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:

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

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:

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

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

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 predefined indoor temperature is exceeded, etc.). The building costs may be linked to the sensitivity analyses and form an integrated part of the entire decision process. An appropriate simulation model including its design variables is selected. Based on the output of the simulation model it should be possible to answer the identified question with the necessary accuracy. The required level of modelling detail will depend on the design phase, where the sensitivity analysis is applied, as well as on the available knowledge of design parameters. In the very early conceptual or preliminary design phases relatively simple calculation methods should be used as the design solutions are not well defined and the knowledge of design parameters limited, while at later design phases more detailed models should be used.

3.2. Screening of design parameters

The second step is by a screening method to determine which design parameters should be included in the sensitivity analysis. This is done by a one-parameter-at-a-time (OAT) method in which the effect of each design parameter on the building performance is evaluated in turn. A performance estimation using "standard values" for all design parameters 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 results obtained by using the standard value and using the extreme values are compared to evaluate which design parameter is building energy performance significantly sensitive to. A design parameter can be considered to be sensitive, if its value can vary considerably. These design parameters are the ones selected for the initial screening. A simple method to determine the design parameter sensitivity is to calculate the output % difference for the extreme values of the design parameter. This "sensitivity index" can be calculated as

$$SI = \frac{E_{max} - E_{min}}{E_{max}} 100\% \quad (1)$$

where E_{max} and E_{min} represent the maximum and minimum output values, respectively, resulting from varying the design parameter over its entire range. If the sensitivity index reaches a defined critical value the design parameter is considered to be important and it is included in the further analysis.

3.3. Assignment of probability density functions

The third step is to assign a probability density function to each design parameter, which is found to be important for building energy performance in the initial screening. In most cases it is possible to estimate the limits for the variation of a design parameter to estimate the most probable value of the parameter within the limits and to choose the most appropriate probability density function. For each design parameter the typical value chosen, variation limits and probability distribution may depend on architectural considerations, technical possibilities or limitations and/or economical consideration or other issues. Results of sensitivity analysis generally depend more on the selected ranges than on the assigned probability distributions. Typically three different probability density functions are used; Uniform, Lognormal and Normal distribution, see Fig. 1.

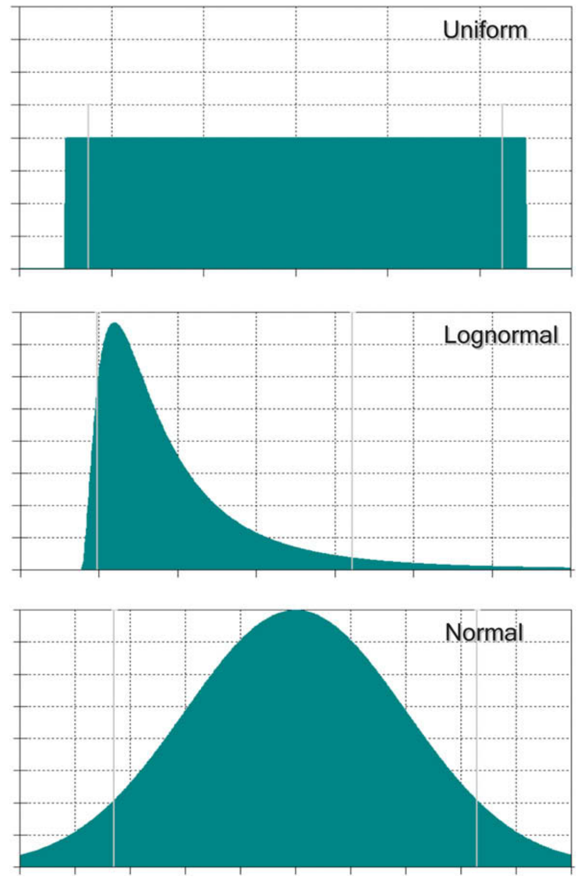

Fig. 1. Probability density distributions usually applied in sensitivity analysis in sustainable building design.

3.4. Generation of design parameter input matrix

The fourth step is to generate input vectors. Various sampling procedures exist among which are: random sampling, Latin hypercube sampling and quasi-random sampling. Control of correlation between variables within a sample is extremely important and difficult, because the imposed correlations have to be consistent with the proposed variable distribution.

The factorial sampling method proposed by [6,1] is applied in this work to generate the input vectors. The method comprises a number of individually randomised one-factor-at-a-time samples of design parameters where all parameters are varied within their variable space in a way that spans the entire space to form an approximate global sensitivity analysis [1,6]. Based on the probability density functions of each parameter random samples of design parameters are generated. Initially each design variable is scaled to have a region of interest equal to [0,1] according to the probability density function chosen for each variable. Each design parameter may assume a discrete number of values, called levels, p, with a distance of equal size, Δ.

A design parameter vector, X_i, with a number of elements equal to the number of design parameters, k, is assigned a random base value (on the discretized grid mentioned above). Then a path of orthogonal steps through the k-dimensional parameter space is "followed". The order of the steps is randomized by selecting a new randomized value for one randomized parameter at a time, while keeping all other design parameters constant. After each step a new design parameter vector is defined, see Fig. 2. This is continued until all design parameters are represented by two different values creating a set of $(k+1)$ independent design parameter vectors.

The procedure is repeated r times creating a set of $r\ (k+1)$ independent design parameters vectors. In order to make sure that the region of variation is reasonably covered for all design parameters a minimum value of $r = 4$ is recommended in the literature, while a value of $r = 10$ is recommended to obtain very reliable

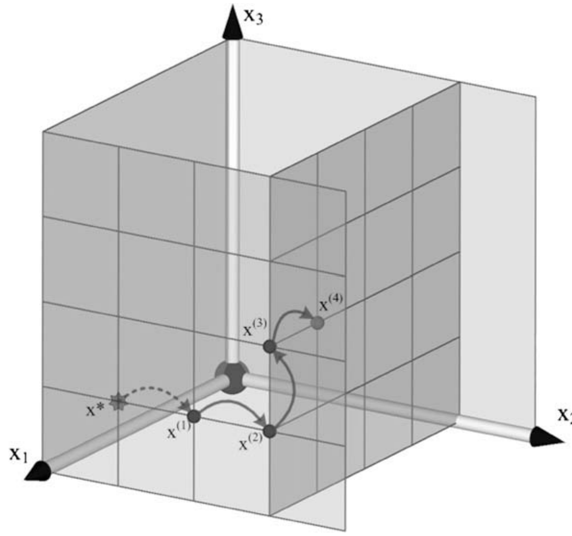

Fig. 2. Illustration of the path of 4 orthogonal steps through a 3-dimensional parameter space to create 4 independent design parameter vector. The random base value, x^*, is used as a starting point for the process.

results [7]. This means that for a case with 20 design parameters the number of design parameter vectors and corresponding simulations to calculate the output values will be in the range of 44–210.

3.5. Calculation of output variable

The fifth step is to create an output variable for each sample of design parameters represented in a design parameter vector. This is achieved by the selected simulation model.

3.6. Assessment of the influence of each design parameter

The last step is the assessment of the influence of each design parameter on the expected value and the variance of the output parameter(s). A number of different techniques can be used, like rank transformation, regression analysis and scatter plots, yielding different measures of sensitivity [1].

The method of "Elementary Effects" [1,2,6], is applied in this work. The method, which can be seen as an extension of a derivative-based screening method, can be characterized as a method with global characteristics. The method has been applied in several areas of building sciences, e.g. natural night ventilation [8], and thermal building simulation [9]. The main purpose of the method is to determine which design parameters may be considered to have effects which are a) negligible, b) linear and additive, or c) non-linear or involved in interactions with other factors.

The method determines the so-called elementary effect EE of a model $y = y(x_1,\dots,x_k)$ with input (design) parameters x_i. The elementary effect for the ith input parameter in a point x is

$$\mathrm{EE}(x_1,\dots,x_k) = \frac{y(x_1,x_2,\dots,x_{i-1},x_i+\Delta,x_{i+1},\dots,x_k) - y(x_1,\dots,x_k)}{\Delta} \quad (2)$$

A number of elementary effects EE_i of each design parameter are calculated based on the generated samples of each design parameter in step four, i.e. the chosen value of r. The model sensitivity to each design parameter is evaluated by the mean value and the standard deviation of the elementary effects:

$$\mu = \sum_{i=1}^{r} |\mathrm{EE}_i|/r \quad (3)$$

$$\sigma = \sqrt{\sum_{i=1}^{r} |\mathrm{EE}_i - \mu|^2/r} \quad (4)$$

where μ is the mean value of the absolute values of the elementary effects determining if the design parameter is important, and σ is the standard deviation of the elementary effects which is a measure of the sum of all interactions of x_i with other factors and of all its non-linear effects. r is the number of elementary effects investigated for each parameter or the number of repetition of the procedure in step four.

The result of the sensitivity analysis is a list of important design parameters and a ranking of the design parameters by the strength of their impact on the output, μ.

4. Design example

In order to illustrate the application of the method described and its potential benefits in an integrated design process, it is demonstrated on a conceptual design proposal for a 7 storey office building.

The office building consists of a ground floor, which is larger than the six upper floors. An atrium is placed in the southern façade from ground floor to the roof, see Fig. 3. The ground floor measures 24.0 m × 32.4 m and is mainly used for an entrance hall, restaurant, office, conference room, cafe and technical appliances. Stairways, toilets and elevators are placed in the centre of the building. The upper floors, measuring 24.0 m × 24.0 m, are conceptually made in the same way although there are slight differences. The 2nd, 4th and 5th floor are designed with the same layout, see Fig. 3. The height of each story is 3.5 m, which gives a total building height of 24.5 m. The gross floor area is $A_{\mathrm{gross}} = 4233.6\ \mathrm{m}^2$. The heated floor area is $A = 3910.8\ \mathrm{m}^2$. The areas of the zones in the building on each floor are listed in Table 1. The ground floor includes a restaurant with a large glazing area. On the south facade of the building the atrium facade has glazing running continuously from the ground level to the 6th floor. In Table 2 the total window area of each floor, including the atrium, is listed as well as the orientation of the windows. The window area relative to the heated floor area is 17%.

The total energy use for heating, ventilation, cooling and lighting in the reference building is calculated by the software programme BE06 to be $E = 107.4\ \mathrm{kW\,h/m^2}$ year (heating 45.9 kW h/m^2 year, ventilation 33.5 kW h/m^2 year, cooling 0 kW h/m^2 year and lighting 28.0 kW h/m^2 year). This is above the present requirements (95 kW h/m^2 year) and some changes in the actual design are necessary in order to reduce the energy use to reach the future requirements.

5. Results of sensitivity analysis

A sensitivity analysis was performed to identify the important design parameters to change in order to reduce the energy use in the reference building. In the analysis a series of parameters were changed and the effect of the changes on the demand for heating, cooling and total energy was evaluated by the software package BE06.

Table 3 shows the design parameters included in the analysis and for each parameter the defined range and distribution. 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

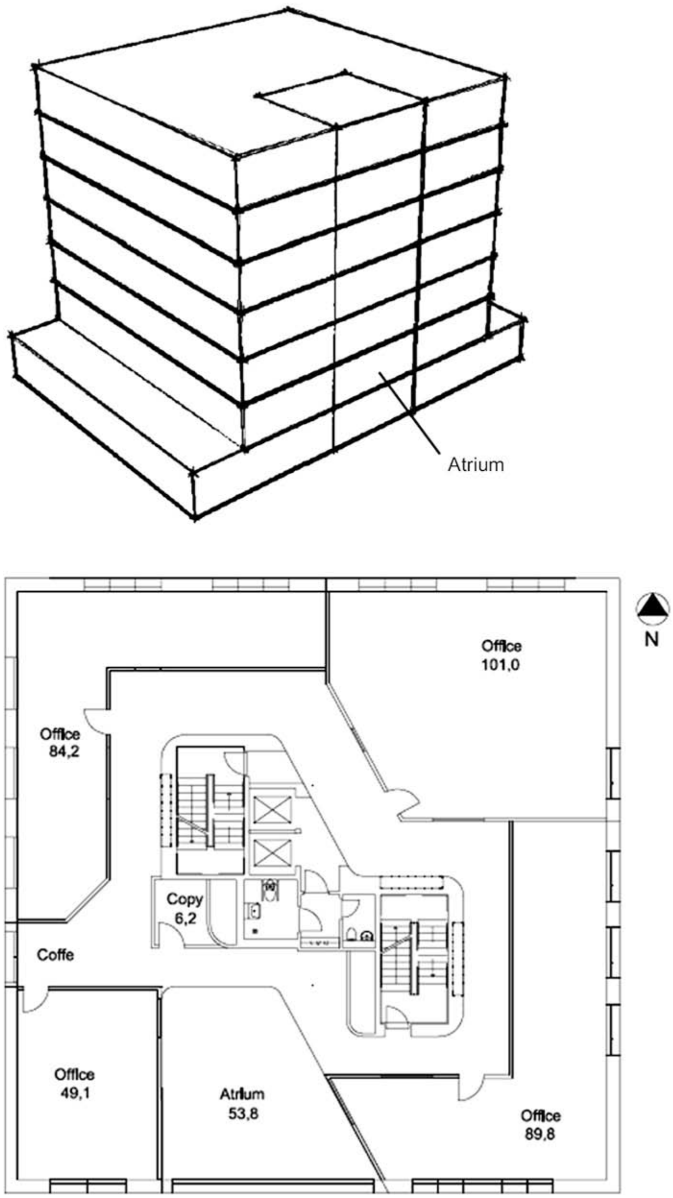

Fig. 3. Sketch and plan drawing of building.

defined by four discrete values. For each design parameter 4 different elementary effects are used, i.e. that for each parameter 4 values of the output variable (energy use) are obtained. With 21 parameters, the minimum number of simulations using Morris' Randomized OAT Design as a Factor Screening Method for Developing Simulation Metamodels [10] is given by

$$N = r\cdot(k+1) = 4\cdot(21+1) = 88 \quad (5)$$

where N is the number of simulations, r is the number of elementary effects per factor, k is the number of design parameters.

Instead of using the minimum number of simulations 10 paths through the design parameter space are explored to give more accurate results. With this number of elementary effects for each parameter, the number of simulations becomes 220.

For the design parameters given in the unit percent in Table 3 the discrete values are the percentage of the values used in the reference building. The usage factor and the installed power concern the lighting zones in the building. The numbers 1–4 for the lighting control system refer to *N*one control, *M*anual control, *A*utomatic control and *C*ontinuous control in BE06.

The parameters in Table 3 are

q_m is the mechanical ventilation rate during daytime in winter
η_{VGV} is the efficiency of the heat recovery
q_n is the natural ventilation rate during daytime in winter
$q_{i,n}$ is the infiltration rate during nighttime in winter
SFP is the specific fan power
$q_{m,s}$ is the mechanical ventilation rate during daytime in summer
$q_{n,s}$ is the natural ventilation rate during daytime in summer
$q_{m,n}$ is the mechanical ventilation rate during nighttime in summer
$q_{n,n}$ is the natural ventilation rate during nighttime in summer
g is the relation between the solar radiation transmitted to the room and the solar radiation reaching the window

Table 1
Floor area of building zones.

	Ground	1st	2nd	3rd	4th	5th	6th
Conference room	100.1	0	0	0	0	0	0
Officers	112.1	237.6	324.1	315.5	324.1	324.1	182.8
Copy rooms	6.5	12.8	6.2	12.8	6.2	6.2	12.8
Café	52.3	0	0	0	0	0	128.4
Restaurant	126.0	38.60	0	0	0	0	0
Kitchen	40.8	37.0	0	0	0	0	0
Technical rooms	7.0	0	0	6.2	0	0	6.2
Administration	22.1	0	0	0	0	0	0
Corridors	235.7	121.2	116.9	112.7	116.9	116.9	117.0
Toilets	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Building core	67.6	67.6	67.6	67.6	67.6	67.6	67.6
$\sum$	777.6	522.2	522.2	522.2	522.2	522.2	522.2

Table 2
Window area and direction.

Floor	North (m^2)	East (m^2)	South (m^2)	West (m^2)
Ground floor	29.7	12.8	47.3	20.8
1st floor	20.2	12.8	46.1	14.2
2nd floor	19.2	12.8	46.1	12.8
3rd floor	20.9	12.8	46.1	12.8
4th floor	19.2	12.8	46.1	12.8
5th floor	19.2	12.8	46.1	12.8
6th floor	20.2	12.8	46.1	12.8
$\sum$	148.6	89.6	323.9	99.0

Table 3
Design parameters for sensitivity analysis, their range and distribution.

	Parameter	Unit	Discrete values			μ	σ
1	Heat capacity	W h/K m^2				120	10
2	U (climate shield)	%	100	83.3	66.7	50	
3	Line loss	%	100	66.7	33.3	0	
4	U (windows)	W/m^2 K	1.5	1.3	1.1	0.9	
5	g-value	n.d.	0.7	0.6	0.5	0.4	
6	Shading	–	0.8	0.6	0.4	0.2	
7	Overheating	°	45	30	15	0	
8	q_m	1/s m^2	0	1	2	3	
9	η_{VGV}	–	0.7	0.75	0.8	0.85	
10	q_n	1/s m^2	0	0.15	0.3	0.45	
11	$q_{i,n}$	1/s m^2	0	0.1	0.2	0.3	
12	SFP	K J/m^3	2.1	1.7	1.3	0.9	
13	$q_{m,s}$	1/s m^2	0	1	2	3	
14	$q_{n,s}$	1/s m^2	0	1	2	3	
15	$q_{m,n}$	1/s m^2	0	1	2	3	
16	$q_{n,n}$	1/s m^2	0	1	2	3	
17	Heat loads	W/m^2				14	2
18	Lighting power	W/m^2	7	8	10	11	
19	Daylight factor	–				2	0.5
20	Light control	–	1(N)	2(M)	3(A)	4(C)	
21	Usage factor	–	1.0	0.9	0.8	0.7	

The results of the sensitivity analysis are shown in Fig. 4. The figure shows the mean value, μ, of the absolute values of the elementary effects determining if the design parameter is important, and the standard deviation, σ, of the elementary effects which is a measure of the sum of all interactions of x_i with other factors and of all its non-linear effects. The dotted wedge in the figure shows the following relation between the mean value and the standard deviation:

$$\sigma = \frac{\mu\sqrt{r}}{2} \tag{6}$$

where μ is the mean value of the elementary effect (kW h/m^2 year), r is the number of elementary effects per design parameter, σ is the standard deviation of the elementary effect (kW h/m^2 year).

The minimum value of $r = 4$ recommended in the literature is used in this example [7] and the dotted wedge in Fig. 4 becomes $\sigma = \mu$.

The location of a point (μ,σ) compared to the wedge given by the above equation provides information about the characteristics of that design parameter. If the point is placed inside the wedge the design parameter has mainly a correlated or/and a non-linear impact on the output (energy use). If the point for a design parameter is placed outside and far from the wedge the impact can be considered as linear and a change in the design parameter would give a proportional change of the output (energy use). If the point is located close to the lines of the wedge it is combination of the two cases.

From the results shown in Fig. 4 it is possible to estimate the influence of each of the design parameters. It is seen that for most of the important parameters the influence on energy use is nearly linear, meaning the impact is almost the same in the whole parameter range. A ranking of the design parameters influence on the sensitivity of the energy use is listed in Table 4. From the ranking it can be concluded, that especially design parameters related to the artificial lighting system and the ventilation system of the building in the winter (heating) season have a significant mean value and therefore a significant influence on the energy use. Also the *U*-values, especially for the windows, have a notable influence.

The sensitivity analysis was also performed with the heating demand as the output parameter. The results of this are shown in Fig. 5.

Table 4
Ranking of design parameters according to their impact on primary energy use.

Rank	Parameter		μ
1	8	q_m	46.30
2	20	Lighting control	44.84
3	11	$q_{i,n}$	24.78
4	12	SFP	22.96
5	18	Lighting power	18.56
6	10	q_n	16.36
7	21	Usage factor	15.94
8	14	$q_{n,s}$	12.58
9	9	η_{VGV}	11.46
10	4	*U* (windows)	10.28
11	15	$q_{m,n}$	7.08
12	2	*U* (climate shield)	6.86
13	19	Daylight factor	5.76
14	5	*g*-value	3.96
15	17	Heat loads	3.96
16	13	$q_{m,s}$	3.86
17	6	Shading	2.12
18	16	$q_{n,n}$	1.96
19	1	Heat capacity	1.36
20	3	Line loss	1.24
21	7	Overheating	1.22

6. Discussion

In the calculation of the primary energy use of the reference office building it was shown that the heating demand (45.9 kW h/m^2 year) was dominating while the ventilation (33.5 kW h/m^2 year) and lighting (28.0 kW h/m^2 year) demand was slightly lower and no demand for cooling existed.

The sensitivity analysis shows which design parameters are the most important ones to change in order to reduce the energy consumption. The results show that lighting control and the amount of ventilation during winter are the two most important parameters that will have the largest effect on the energy use. This means that introduction of lighting control according to daylight levels and demand controlled ventilation in the heating season are two technologies that should be considered in the next design step.

It can also be seen that even if the heating demand is dominating the ranking of design parameters reducing the heat loss from the building is quite low. If an analysis is done for the heating demand alone instead of for the total energy use it can be seen from

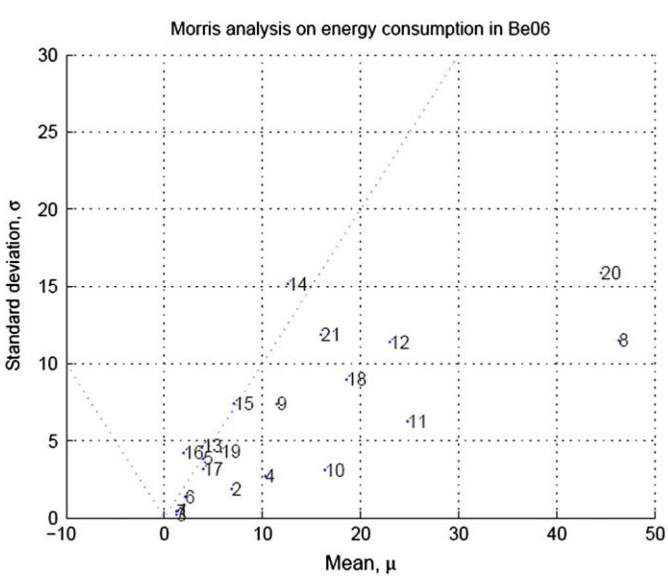

Fig. 4. Influence of design parameters on the total energy use.

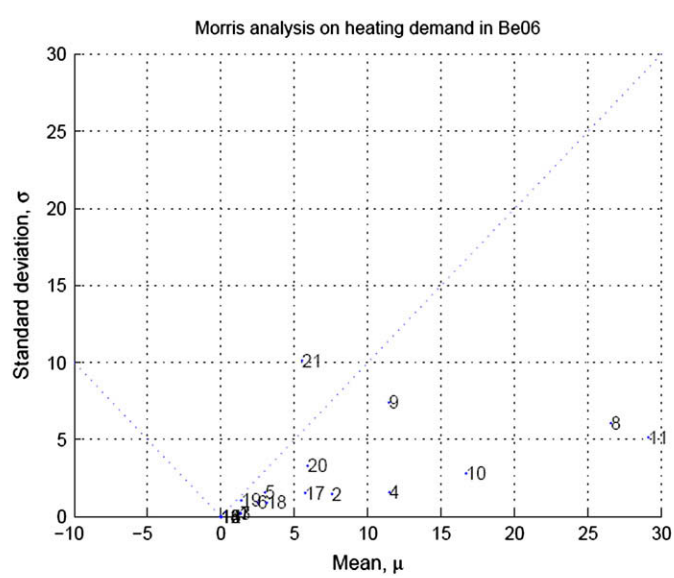

Fig. 5. Influence of design parameters on the heating demand.

Fig. 5 that the ranking of parameters changes a lot. Now design parameters related to ventilation in the heating season are the most important ones, while improvement of insulation levels and cold bridges still only will have a minor influence.

As the cooling demand does not exist it can also be seen that design parameters influencing the heat load of the building naturally have the lowest ranking.

It can be concluded that a sensitivity analysis in the early stages of the design process can give important information about which design parameters to focus on in the next phases of the design as well as information about the unimportant design parameters that only will have a minor impact on building performance.

The sensitivity analysis will improve the efficiency of the design process and be very useful in an optimization of building performance.

References

[1] Saltelli A, Chan K, Scott EM. Sensitivity analysis. John Wiley & Sons, ISBN 047 1998 923; 2000.

[2] Saltelli A, Tarantola S, Campolongo F. Sensitivity analysis as an ingredient of modeling. Statistical Science 2000;15(4):377–95.

[3] Hamby DM. A review of techniques for parameter sensitivity analysis of environmental models. Environmental Monitoring and Assessment 1994;32:135–54.

[4] Lam JC, Hui SCM. Sensitivity analysis of energy performance of office buildings. Building and Environment 1996;31(1):27–39.

[5] Lomas KJ, Eppel H. Sensitivity analysis techniques for building thermal simulation programs. Energy and Buildings 1992;19(1):21–44.

[6] Morris MD. Factorial sampling plans for preliminary computational experiments. Technometrics 1991;33(2):161–74.

[7] JRC. Joint Research Centre of the European Commission, Ispra, Italy; 2004. http://sensitivity-analysis.jrc.cec.eu.int/.

[8] Breesch H, Janssens A. Uncertainty and sensitivity analysis of the performances of natural night ventilation. In: Proceedings of Roomvent 2004, 9th international conference on air distribution in rooms, Coimbra, Portugal; 5–8 September 2004.

[9] De Wit MS. Identification of the important parameters in thermal building simulation models. Journal of Statistical Computations and Simulations 1997;57:305–20.

[10] Saltelli A, Tarantola S, Campolongo F, og Retto M. Sensitivity analysis in practice – a guide to assessing scientific models. John Wiley & Sons, ISBN 0470870931; 2004.

[11] Energy use in buildings. SBi-instructions 213. Danish Building Research Institute; 2005 (in Danish).