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Model uncertainty and sensitivity analysis for thermal comfort prediction

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1. Abstract

Building Performance Simulation (BPS) is poorly used to support informed decision making between different design options nor is it used for building and/ or system optimization. Currently BPS is only used for code compliance during the detailed design [Wilde, 2004].
The approach of this research by using an existing tool as initial prototype is rapid prototyping to make incremental improvement of BPS.
This paper elaborates the above in more detail in particular by focusing on an uncertainty and sensitivity analysis for thermal comfort prediction.
A case study is described to evaluate the necessity of the use of uncertainty and sensitivity analysis in BPS. For that purpose an in the Netherlands well-known and commonly-used simulation tool for the detailed design is chosen. Furthermore, a range of results reflecting the impact of UA and SA are presented.

2. Introduction

The reliability of simulation results, due to the assumptions a designer has to take is still not clear. This paper summarizes the results of a case study considering an UA and SA regarding thermal comfort. The sources of uncertainties when assessing thermal performance can be divided in four categories: abstraction, databases, modeled phenomena and solution methods [Macdonald et al., 1999]. Main source is hereby the abstraction group that comprises simplification or concessions to be made in order to accommodate the design. This group can be easily assessed using the set-up described in the methodology.

3. Methodology

3.1 Setup

To verify the breadboard construction with a commercially available, industry strength, and extensively used, BPS tool called VA114 was coupled with an external research type software tool called Simlab. A case study was performed based on a hypothetical building which is part of an international test method BESTEST for assessing the accuracy of BPS tools with respect to various building performance parameters. This case study was executed 200 times; altogether 46 input parameters were varied per simulation. For generating the sample matrix the latin hypercube sampling (LHS) was selected. The LH sampling is a particular case of stratified sampling which is meant to achieve a better coverage of the sample space of the selected input parameters [Saltelli et al., 2005]. For the 200 simulations and the 46 variables

three different input files were necessary for the BPS tool. The generation of the input files was done via one macro in excel.
The simulation itself can be easily started by a batch file providing those created input files.

3.2 Thermal comfort

To assess thermal comfort in a building numerous techniques exist to analyze the performance. In VA114 there is one main criterion available which is called GTO-criterion. It is a Dutch criterion, published by the Rijksgebouwendienst in 1991 [ISSO 2004]. The weighted overheating or under heating hours (Dutch: Weeguren or GTO) is based on the Fanger- Model. In this criterion the extent in which a PMV of +0,5 is exceeded is expressed by a factor WF(weegfactor):

$$WF = 0{,}47 + 0{,}22 * PMV + 1{,}3 * PMV^2 + 0{,}97 * PMV^3 - 0{,}39 * PMV^4 \qquad (1)$$

For instance, for a PMV value of + 0.5 the WF factor equals 1,0 ; for a PMV value of +1.0 the WF is 1,6 and for a PMV of +2,0 the WF equals 8,7. Each hour during operation time this factor is determined. The sum of these hourly factors over the year results in the weighted overheating hours. In case the system is bad dimensioned the number of weighted overheating hours can be rather high, even higher than the number of operation hours.
In case the number of weighted overheating hours stays below 150h per year the indoor conditions are in the range. The same is valid for "the weighted under heating hours". The maximum number of 150h only applies to the DeBilt weather data of year 1964/65.

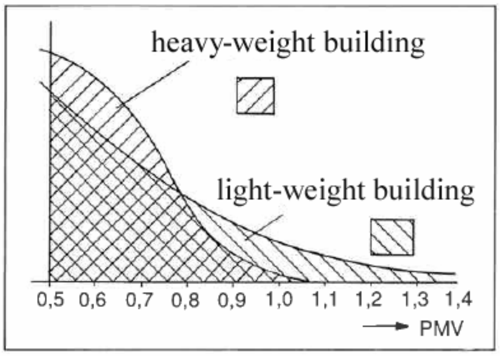

Figure 1: number of hours that a certain PMV value appears for two different kinds of buildings

The exceeded PMV value of 0.5 depends on the mass of the building [ISSO 1990]. For this reason the simulation of the case study was not done with the light weight case 600 but instead with the corresponding heavy case 900.
The graphic on the right side taken from [ISSO 1990] shows the distribution of the exceeded PMV values of two different types of buildings. The light building shows obviously a more overshooted amount of PMV=0.5 than the heavy building.
However, thermal comfort is easier to express in heavy buildings, other problems arise with the number of operating hours. The GTO value of 150h per year is calculated with an operation time of 8h per day. The limit of 150 h arises out the 2000h/year (8h/d* 5d/week*52weeks/year) *5% [percentage of below/ upper]*1.5 [averaged value].
Another issue is that temperatures are controlled on the air temperature and not on the comfort temperature. Even at (air) set points of 23,5 C there is enough reasons to give PMVs outside the region -0,5 < PMV < +0,5 and for that reason to give over- and under heating.
More problems appear because of the set points of the BESTEST case which are set to 20 and 27 degrees. Also the humidity of the indoor air has an influence on the PMV; in the BESTEST-case there is no moisture production, no mechanical ventilation, only infiltration; therefore the absolute humidity is about the same as outside.
To sum up it can be concluded that even with the heavy weight building the GTO of 150h won't be complied. The demonstrated results will therefore less focus on the thermal conditions and their range regarding the applicability but give more an impression about the sensitivity of the parameters in general.

3.3 Monte Carlo analysis (MCA)

The Monte Carlo analysis (MCA) which is an external global analysis method is one of the most commonly used methods to analyze the approximate distribution of possible results on the basis of probabilistic inputs. The MCA is a black box approach- there is no code modification necessary; thus it is easy to implement to any desired tool [Lomas et al. 1991].

Comparable to [Hopfe et al., 2006] the following steps can be listed in general:

1. Description of a target function and consideration of the essential input.
2. Assignment of a normal distribution to the selected variables.
3. Generation of a matrix of inputs with the normal distribution through a suitable design.
4. Evaluation of the model and computation of the distribution.
5. Selection of (a) method/s for assessing the influence or relative importance/ sensitivity of each input factor based on the target function.

3.4 Uncertainty analysis

The UA specifies the general uncertainty in model prediction due to the imprecisely knowledge of input variables. The MCA is one simple analysis, where the expected averaged E and the variation V of the output Y are determined by following formulas:

$$E(Y) = \frac{1}{N}\sum_{i=1}^{N} y_i ; \qquad (2)$$

$$V(Y) = \frac{1}{N-1}\sum_{i=1}^{N} [y_i - E(Y)]^2 ; \qquad (3)$$

where N = number of samples and i = number of input parameter.

3.5 Sensitivity analysis

The SA determines the contribution of individual input variable to the uncertainty in model prediction.

There are several different techniques in Simlab available for sensitivity analysis. The chosen one for demonstrating the results is the partial correlation coefficient (PCC). The PCC provides a measure of the linear relation between any given input X and the output, cleaned of any effect due to correlation between X and any other input [Saltelli et al., 2005].

First the two models were created:

$$\hat{Y} = b_0 + \sum_{h \neq j} b_h x_h \qquad (4)$$

$$\hat{X}_j = c_0 + \sum_{h \neq j} c_h x_h \qquad (5)$$

The results of those regressions were used to define two new variables: $Y - \hat{Y}$ and $X_j - \hat{X}_j$. The partial correlation between Y and X is now defined as a correlation coefficient between $Y - \hat{Y}$ and $X_j - \hat{X}_j$. The PCC quantifies the relation between input and output parameter in a manner that the correlation between the input parameter (X_j) and every other parameter ($X_j, i \neq j$) is not possible.

4. Case study

The following paragraph will summarize the building characteristics and the boundary conditions of the case study. All input parameter are assumed to be normal distributed; the standard deviations are derived by several sources in literature.
Instead of the Drycold weather file usually taken for the BESTEST case, the weather file was changed into DeBilt weather data.
The temperature set points were fixed to 21 degrees for heating and 25 degrees for cooling.

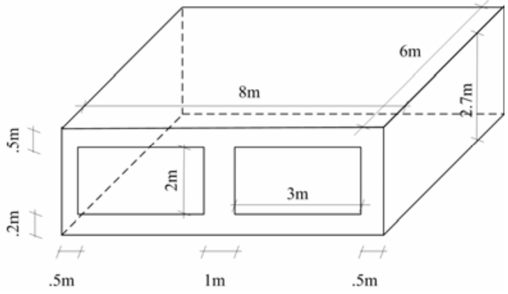

Figure 2 Geometry case study

4. 1 Thermal model

Table 1 shows the material properties varied with their mean and standard deviation. The values for solar absorptivity, inside and outside emissivity, casual gains and infiltration rate are summarized in the Appendix.

Tabel 1: Material properties: mean (μ) and standard deviation (σ) of conduction (λ), density (ρ), specific heat capacity c and thickness (t)

MATERIAL		λ (W/mK)	ρ (kg/m^3)	c (J/kgK)	t (m)
Wall					
Concrete block	μ	0.51	1400.00	1000.00	0.1
	σ	0.23	364.00	107.00	0.01
Foam insulation	μ	0.04	10.00	1400.00	0.0615
	σ	0.01	3.90	389.20	0.00615
Wood siding	μ	0.14	530.00	900.00	0.009
	σ	0.06	132.50	171.00	0.0009
Floor					
Concrete slab	μ	1.13	1400.00	1000.00	0.08
	σ	0.51	364.00	107.00	0.008
Insulation	μ	0.04	30.00	2000.00	1.007
	σ	0.01	9.90	556.00	0.1007
Roof					
Plasterboard	μ	0.16	950.00	840.00	0.01
	σ	0.06	319.20	115.08	0.00
Fibreglas quilt	μ	0.04	12.00	840.00	0.11
	σ	0.00	0.12	10.08	0.01
Roofdeck	μ	0.14	530.00	900.00	0.02
	σ	0.01	5.30	37.80	0.00

The calculated values in table 1 are comparable estimations taken from Macdonald [Macdonald, 2002]. Besides the thickness that is calculated due to a lack of information on the exact properties. The range of possible deviations in the geometry has been estimated at [-0.02, 0.02] m [de Wit, 2001].

Furthermore, Macdonald derived for solar absorption an average value from [Clarke et al., 1990], which is based on a collection of data of thermo physical properties from standards and measurements [Breesch, 2006].

The output provided by VA114 regarding thermal comfort is number of comfort hours above 25 and 28, and the GTO value. Due to the limit of pages only the results of overheating hours are presented.

4.2 Results uncertainty analysis (UA)

The MCA was executed with 200 simulations. For the analysis of the results an executable was implemented with Matlab. Representative results are given for the weight overheating and under heating hours. Last one is demonstrated in the Appendix. The UA shows the distribution of the output which is caused by the uncertainties in the input. An uncertainty of the output causes a wide spread which is shown in the Histogram in figure 2. The line in figure 1 shows an estimated normal curve of distribution. Figure 2 demonstrates how far the distribution matches the assumptions by illustrating a normality plot. Due to the fact that the results follow the line it can be concluded that the output for weight overheating hours is normal distributed.

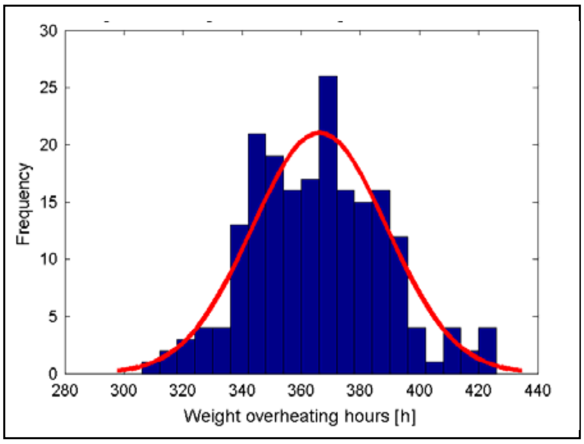

Figure 2: Histogram - weight overheating hours

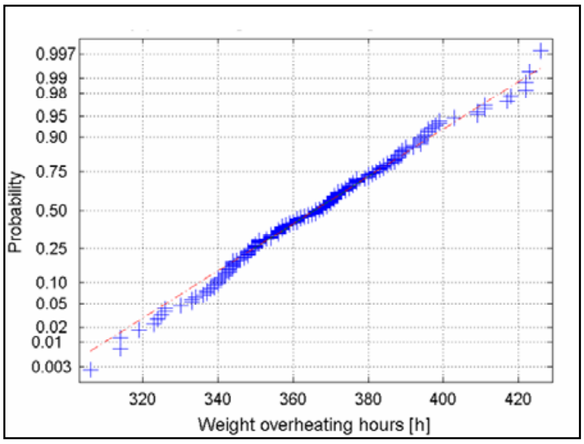

Figure 3: Normality plot - weight overheating hours

4.3 Results sensitivity analysis (SA)

For the SA Simlab was used to analyze the results. The results for all 46 parameters can be found in tables and figures in the Appendix.

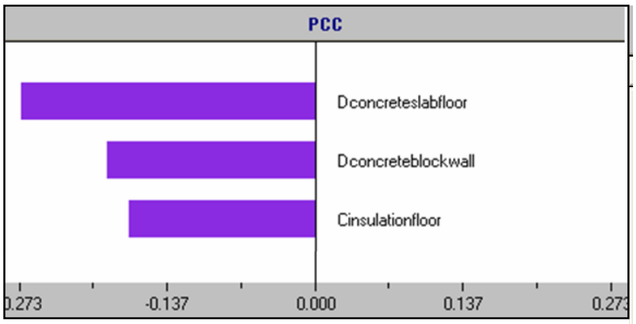

Figure 4: Results SA

For the sensitivity analysis results are summarized for the first three positions. The higher the value of the variable the more sensitive it is. As explained before the results are interpreted for the PCC coefficient. Figure 4 shows an extract of the three most sensitive parameters. It also indicates how sensitive each parameter is. Furthermore it can be seen which relation a parameter has with the output, positive or negative. The most sensitive one is the density of the concrete floor followed by the density of the concrete wall and the conductivity of the insulation of the floor.

5. Conclusion

The BESTEST 900 is simulated 200 times with the BPS tool VA114; parameters with a possible effect on the uncertainty are identified and analyzed with the PCC.
This approach is currently applied to another simulation tool in order to lead to more general conclusions. Up to date, a number of preliminary conclusions can be taken:
Several adjustments were made in order to receive more reasonable results; the set points were changed as well as the weather data.
In general, the calculated GTO value appears to be as criteria difficult for showing comprehensible results.
The density of the concrete floor is defined as most sensitive parameter, having the largest important impact on the thermal behaviour of the case study; whilst the specific heat capacity is the parameter with the fewest impact (see Appendix).

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Appendix

Table A.1
Mean and standard deviation

SPECIFICATION		**μ**	**σ**	**%**
Solar Absorptivity	ROOF	0.6	0.006	1.0
	FLOOR	0.6	0.006	1.0
	WALL	0.6	0.006	1.0
	GLASS	0.6	0.006	1.0
Inside Emissivity	ROOF	0.9	0.0198	2.2
	FLOOR	0.9	0.0198	2.2
	WALL	0.9	0.0198	2.2
	GLASS	0.9	0.0198	2.2
Outside Emissivity	ROOF	0.9	0.0198	2.2
	FLOOR	0.9	0.0198	2.2
	WALL	0.9	0.0198	2.2
	GLASS	0.9	0.0198	2.2
Casual Gains	IHG	200	26.4	13.2
Infiltration AC Rate	IAC	0.5	0.17	34.0

Table A.2
Output SA PCC

ORDER	**PARAMETER**		**PCC**
1	density	concreteslab floor	-0.273
2	density	concreteblock wall	-0.193
3	conductivity	insulation floor	-0.172
4	density	fiberglas roof	-0.156
5	inside emissivity	glazingcase	0.147852
6	conductivity	concreteblock wall	-0.14
7	outside emissivity	roofcase	-0.134
8	specific heat capacity	foaminsulation wall	0.13202
9	conductivity	concreteslab floor	-0.129
10	specific heat capacity	concreteblock	-0.119
11	inside emissivity	wallcase	-0.118
12	conductivity	woodsiding wall	0.117021
13	conductivity	roofdeck	0.107884
14	thickness	concreteblock wall	-0.0833
15	thickness	concreteslab floor	-0.0815
16	specific heat capacity	concreteslab floor	-0.0791
17	thickness	insulation floor	0.0696597
18	density	plasterboard roof	0.066483
19	specific heat capacity	fiberglas roof	0.0648089

Table A.2
Output SA PCC (continue)

ORDER	PARAMETER		PCC
20	conductivity	fiberglas roof	0.062979
21	specific heat capacity	woodsiding wall	0.0611844
22	outside emissivity	wallcase	0.0600108
23	density	insulation floor	-0.0582
24	density	woodsiding wall	0.058167
25	density	foaminsulation wall	-0.0562
26	inside emissivity	roofcase	0.054606
27	thickness	woodsiding wall	0.0457563
28	solar absorptivity	wallcase	-0.0438
29	infiltration AC rate	building	-0.0418
30	specific heat capacity	plasterboard roof	0.040849
31	thickness	roofdeck	0.0373677
32	thickness	fiberglas roof	0.0293877
33	casual gains	building	0.0291379
34	inside emissivity	floorcase	-0.0286
35	solar absorptivity	roofcase	-0.0256
36	conductivity	foaminsulation wall	0.0247197
37	specific heat capacity	roofdeck	-0.0234
38	solar absorptivity	glazingcase	-0.0219
39	thickness	plasterboard roof	0.0211358
40	outside emissivity	glazingcase	-0.0191
41	outside emissivity	floorcase	0.0177971
42	density	roofdeck	-0.0169
43	solar absorptivity	floorcase	-0.0165
44	conductivity	plasterboard roof	0.012174
45	thickness	foaminsulation wall	-0.0104
46	specific heat capacity	insulation floor	0.00708278

Figure A.1/A.2
Histogram and normality plot – weight under heating hours

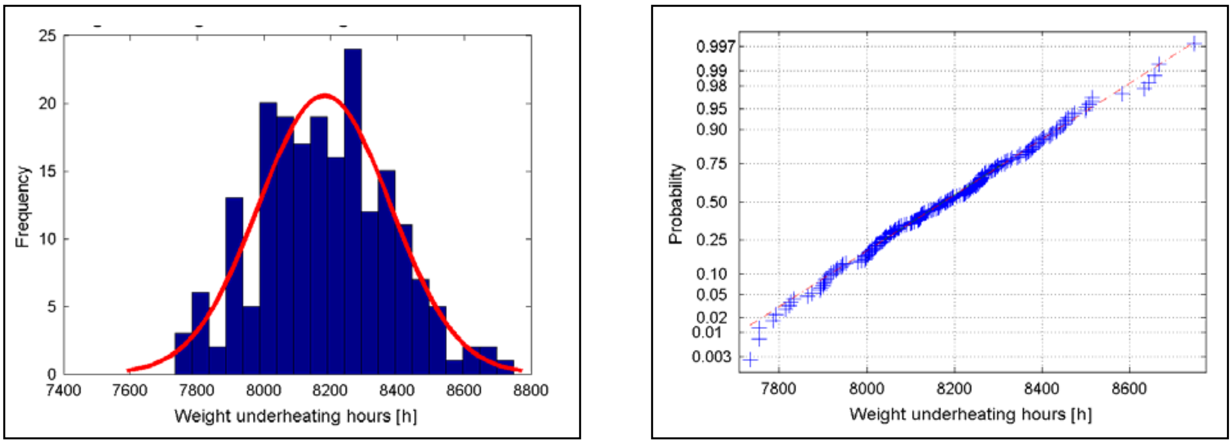

Figure A.3
Comparison SA weight over- and under heating hours

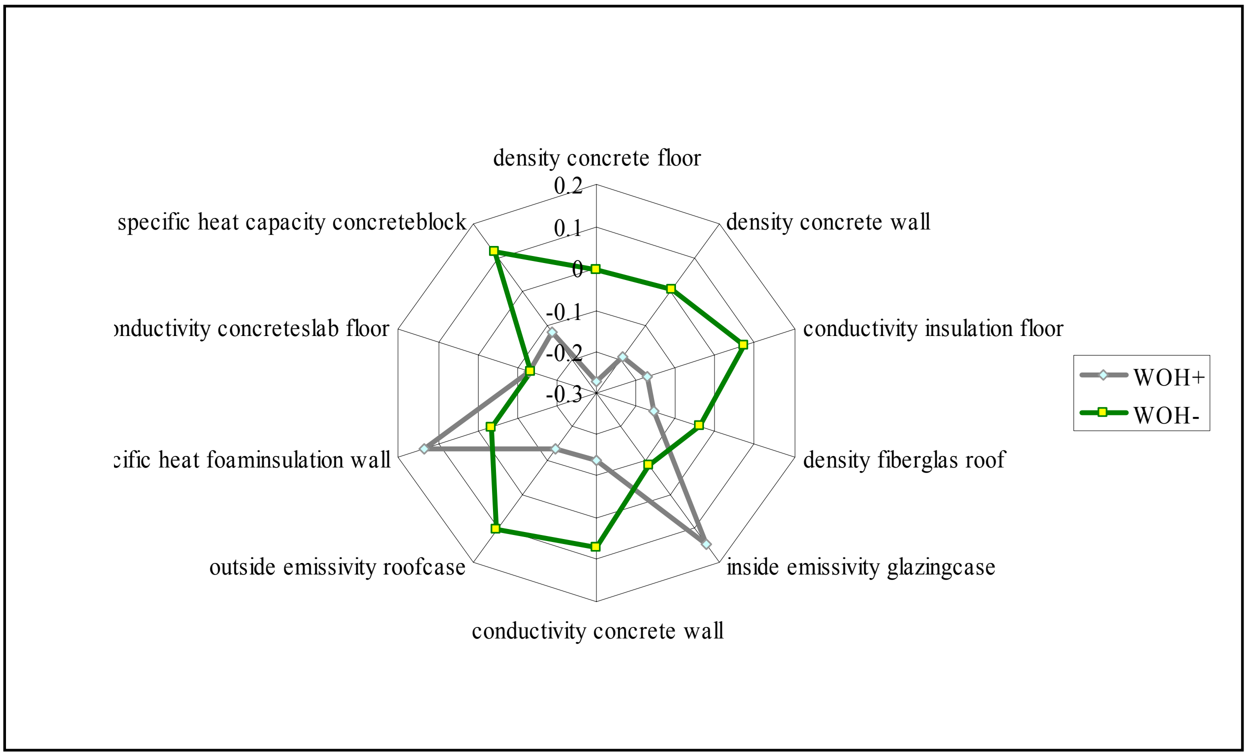

Figure A.4
Graphical output SA PCC