INFLUENCE OF MODELING UNCERTAINTIES ON THE SIMULATION OF BUILDING THERMAL COMFORT PERFORMANCE

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ABSTRACT

In this paper, the parameters in a building thermal simulation model are tracked, which are subject to modeling uncertainty, i.e. uncertainty arising from commonly applied physical assumptions and simplifications. As an example, the simulation of the thermal comfort performance of a naturally ventilated office building without cooling plant is analyzed. The sensitivity of the simulated performance to the uncertainty in the parameters is investigated with a factorial sampling technique, which not only estimates the mean parameter effects, but also reveals the relative importance of non-linear effects and parameter interactions.

INTRODUCTION

In the design stage of an office building, a principal relies on a prediction of the future building performance to guide his decisions. For an important performance aspect, i.e. thermal comfort, building physics consultants currently supply deterministic predictions. That is, only one single performance value is calculated, as if the design specifications determine this value completely and without uncertainty. However, uncertainty is introduced from several sources, see Table 1.

Table 1 Sources of uncertainty in building performance predictions.

1	Buildings are not constructed exactly to specifications.
2	At the time a performance prediction is required, the design is generally not yet complete. The future design decisions are not known and therefore have an uncertain effect on the predicted performance.
3	The complexity of the physical processes to be modeled necessitates assumptions and simplifications, which introduce model uncertainty.

Neglect or underestimation of the resulting prediction uncertainty fails to reveal the reliability of the predictions and may lead to detrimental design decisions.

In order to assess this reliability, an uncertainty analysis is required. As uncertainty is caused by a lack of information, it is important to start its analysis with a careful investigation of the information that is made available to the building physics consultant.

To understand the structure of this information, it is important to realize that the final product of a building process is the physical realization of the building. A performance prediction at the design stage, required to show compliance with a performance demand, can be interpreted as the outcome of a (simulation) test-experiment on this product, carried out under well-defined test conditions. This means that the consultant uses two separate sets of data to conduct a (simulation) experiment:

1. Design specification, including of e.g.
    - shape of the building
    - materialization of the building
    - specification of the plant
2. Test-conditions (scenario), including e.g.
    - (meteo) climate time series
    - behavior of occupants
    - control setpoints
    - other data concerning the operation of the building.

From these two sets of data, the performance prediction can be assessed as shown in Fig. 1. The figure also shows the places where uncertainty is introduced. The process uncertainty typically involves uncertainty sources of type 1 and 2 (see Table 1). The modeling uncertainty is equal to uncertainty type 3.
No uncertainty is introduced in the scenario-branch of the scheme. As a sensible interpretation of the performance assessment is only possible in relation to the test-conditions that were applied, it is imperative that these conditions are unequivocal to all actors involved in the calculation and interpretation. Any form of uncertainty (or vagueness in this context) on either side should be avoided.

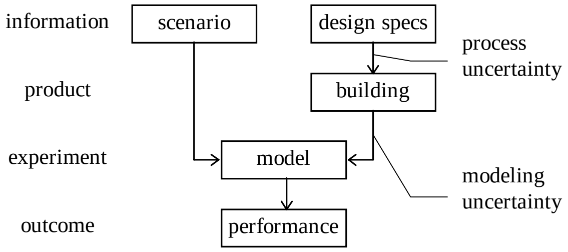

Fig. 1 Schematic representation of a building performance simulation process.

In this paper we will only address the analysis of modeling uncertainty. In other words, we will assume that the shape and materialization of the building are known up to the smallest detail, as are the relevant properties of both materials and prefabricated components in the building.

The first step in an effective uncertainty analysis is a sensitivity study to obtain a crude estimate of the impact of the uncertainties and to reveal the main contributors to the resulting uncertainty. In a subsequent stage, all effort can then be focused on these main contributors.

This paper reports the results of a sensitivity study on the thermal comfort performance of a single room in an office building. As mentioned earlier, only the sensitivity for modeling uncertainties is investigated. This distinguishes this study from the previous sensitivity analyses described in (Lomas, Eppel, 1992, Jensen, S.O, 1994, Rahni e.a., 1995 and Furbringer, 1994) These studies all concerned model validation projects. The aim was to quantify the uncertainty in the model calculations due to a lack of knowledge about the material and component properties of the experimental test facility on the one hand and uncontrolled or unmeasured scenario specifications on the other hand. Modeling uncertainties as defined in this paper were obviously *not* investigated in these studies, as a validation study aims to investigate to what extent the model calculations explain the experimental results without having to reach for modeling uncertainty.

Lomas (Lomas, 1992) and Martin (Martin, 1993) conducted sensitivity analyses on thermal building simulation results in order to estimate the effects of uncertainties in the building design stage. They focused on annual energy consumption rather than thermal comfort and their studies were restricted to variations of the input parameters of one or more particular building simulation tools. This paper aims at a more systematic analysis of modeling uncertainty, independently of a specific simulation tool.

THERMAL COMFORT PERFORMANCE

In this paper, the output of the building simulation is thermal comfort performance, as defined in the guidelines of the Rijksgebouwendienst (a Dutch government building agency) (RGD, 1979). For all office buildings, erected under the commission of the Rijksgebouwendienst, an air temperature of 25 ^{o}C should not be exceeded during more than, on average, 5% of the total number of working hours/year. In accordance with this guideline, the comfort (dis)performance *C* can be defined as the number of hours/year that the air temperature level of 25 ^{o}C is exceeded. Although the RGD-directives were recently refined and expanded, the comfort performance definition according to the earlier guideline will be used here as it is lucid and well suited for the purpose of this study.

CASE DESCRIPTION

This case study considers the final design stage of a three storey office building in a sub-urban/urban environment. To investigate the thermal comfort performance in summer conditions, a room is selected at the top floor, oriented to the east (*Fig. 2*)

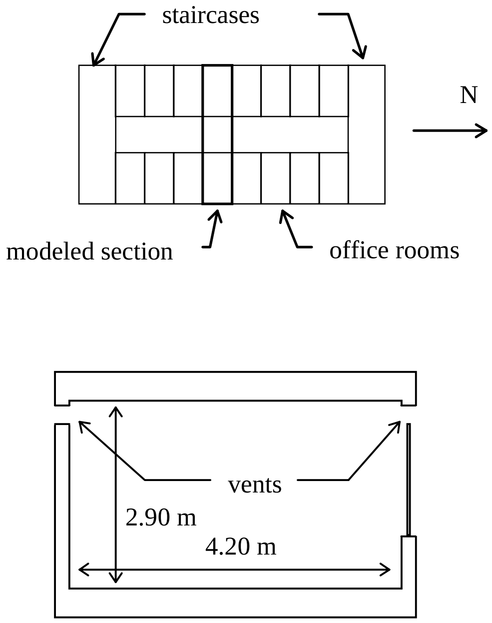

Fig. 2 (a) plan of the top floor and (b) a vertical cross section of the office space in question. The width of the office spaces is 2.70m; roof height of the building is 10m above ground level (3 storeys).

The design specifications can be summarized as: an office building with heavy interior walls, double glazing, external solar shading and no cooling plant.
Specific features of the scenario are: office hours from 8.00-18.00 , 7 days a week, total internal heat production of 20 W/m^2 during office hours, automatic control of the solar shading, external windows and internal doors closed at all times, doors to staircases at both sides of the corridor closed at all times.

MODELING

Fig. 2 shows the section of the building that is actually modeled. All adjacent spaces are assumed to be identical to those in this section.

The heat balance equation for a space enclosed by the building fabric is:

$$\rho c V \frac{\partial}{\partial t}\overline{T}_{air} = \boldsymbol{\Phi}_m c_p\left(T_{in} - \boldsymbol{T_{out}}\right) + \\ + \sum_j \boldsymbol{\alpha^c_{int,j}}\left(T_{\text{int},j} - \overline{T}_{air}\right)A_j + \\ + \boldsymbol{Q^c_{sol}} + \boldsymbol{Q^c_{srce}} \qquad \textbf{(1)}$$

where:

$\overline{T}_{air}$ volume averaged air temperature
$\boldsymbol{\Phi_m}$ air mass flow through space
T_{in} temperature of incoming air
$\boldsymbol{T_{out}}$ temperature of outgoing air
j index of wall component
$\boldsymbol{\alpha^c_{int}}$ internal convective heat transfer coefficient
T_{int} internal surface temperature of wall component
A area of wall component
$\boldsymbol{Q^c_{sol}}$ convective part of solar gain
$\boldsymbol{Q^c_{srce}}$ convective part of internal heat production

The temperature field T_j in wall component j of the building fabric is modeled by the 1-dimensional heat conduction equation:

$$\frac{\partial}{\partial t}\rho c T_j = -\frac{\partial}{\partial x}\left(\lambda \frac{\partial T_j}{\partial x}\right) \qquad \textbf{(2)}$$

with the following boundary conditions:

At the interior of a building space:

$$-\lambda \frac{\partial T_j}{\partial n}\bigg|_{int} = \boldsymbol{\alpha}^c_{int,j}\left(\overline{T}_{air} - T_{\text{int},j}\right) + \boldsymbol{q_{sol,j}} + \\ + \boldsymbol{q^r_{srce,j}} + \sum_{k,k\neq j} q^r_{jk} \qquad \textbf{(3)}$$

where:

n surface normal
$\boldsymbol{q_{sol}}$ solar heat flux, absorbed at surface
$\boldsymbol{q^r_{srce}}$ sum of radiant heat fluxes from heat sources
q^r_{jm} net radiant heat flux from surface of component m irradiating this surface j

At the exterior of the building:

$$-\lambda \frac{\partial T_j}{\partial n}\bigg|_{ext} = \boldsymbol{\alpha^c_{ext,j}}\left(\boldsymbol{T_a} - T_{ext,j}\right) + \boldsymbol{q_{sol,j}} + \\ + \sum_k \varepsilon_j F_{jk}\sigma\left(\boldsymbol{T_k}^4 - T^4_{ext,j}\right) \qquad \textbf{(4)}$$

where:

$\boldsymbol{\alpha^c_{ext}}$ external convective heat transfer coefficient
$\boldsymbol{T_a}$ local ambient temperature
$\boldsymbol{q_{sol,j}}$ solar heat flux absorbed at surface
ε_j longwave emissivity of surface j
F_{jk} view factor from emitter k to surface j
σ Stefan-Boltzman constant
$\boldsymbol{T_k}$ radiant temperature of emitter k
T_{ext} temperature of external wall surface

At a thin air layer:

$$-\lambda \frac{\partial T_j}{\partial n}\bigg|_{air\ layer} = \frac{1}{\boldsymbol{R_t}}\left(T_{s,k} - T_{s,j}\right) \qquad \textbf{(5)}$$

where:

$T_{s,k}$ surface temperature of wall component k at opposite side of the gap
$T_{s,j}$ surface temperature of this wall component j
$\boldsymbol{R_t}$ total heat resistance of the air layer.

Formulation of one equation of type (1) for each space and one equation of type (2) with appropriate boundary conditions for each building fabric component yields a set of (partial) differential equations from which the temperature field in the building can be solved as a function of time.

In equations (1) till (5), the terms or parameters with modeling uncertainty are boldfaced. They are discussed in the following sections. Furthermore, the range or domain used in the sensitivity analysis is reported for each uncertain parameter or sub-model. Due to the limited space in this paper, however, only an outline of the approach towards modeling uncertainty can be presented. A full treatment can be found in De Wit, 1997b.

VENTILATION HEAT FLOWS

(term 1 in (1))

In this section, the uncertainty in two variables is discussed: the air mass flow Φ_m and the temperature of the outgoing air T_{out}.

Air mass flow

Under the specified scenario conditions, modeling uncertainty in the air mass flow through the office spaces is only determined by the set of wind pressure coefficients and the wind reduction factor.

The wind reduction factor is the ratio between the meteo wind speed, measured at 10m above ground level, and the local wind speed at a given reference level, to which the pressure coefficients are related. This reference level is usually chosen equal to the building roof height, in this case 10m. State of the art models for this parameter are not valid at roof height in urban environments (e.g Wieringa, 1983, Wieringa, 1993, Plate, 1995).

However, the AIVC-guidelines (Liddament, 1986) provide different models to calculate the wind reduction factor at this level in four terrain classes. The validity of these models is questionable, but in this paper it will be assumed that at least the classification makes some sense, i.e. that it is expected that the variation within one class does not (significantly) exceed the variation between classes. Therefore, the range for the wind reduction factor in the sensitivity study was set to the width of the 'urban' terrain class: [0.5, 0.7].

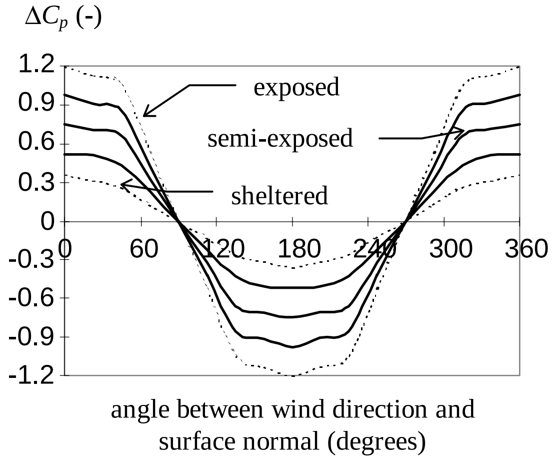

Fig. 3 Pressure difference coefficient data for different shielding classes. The drawn lines indicate the three data sets that were used in the sensitivity analysis.

A similar line of reasoning was followed for the wind pressure coefficients. A significant body of experimental data exists on isolated buildings, but for more complex configurations with low rise buildings, no systematic data are available. Therefore, the AIVC-guidelines were consulted again on this subject. Fig. 3 shows the wind pressure coefficient sets for three terrain classes according to the AIVC and the three sets that were used in this sensitivity study.

Temperature of the outgoing air

In building simulation models, the air temperature in a space is commonly assumed to be uniform, which implies $T_{out} = \overline{T}_{air}$. However, a temperature difference up to several degrees centigrade over the height of a room is a normal phenomenon under summer conditions. In several studies (Chen,1988; Nielsen,1982; Holmes, Caygill, 1973 and Chen, Moser and Suter,1992) an (approximately) proportional relation between air-conditioning load and the vertical temperature difference is proposed. In analogy, the vertical temperature difference ΔT over the space is modeled in this paper as:

$$\Delta T = \xi\, Q_{tot} \qquad \textbf{(6)}$$

where Q_{tot} is the sum of all positive heat flows into the space. Additionally, the temperature profile over the space height is assumed to be linear. As all vents are located near the ceiling, T_{out} is modeled as:

$$T_{out} = \overline{T}_{air} + \tfrac{1}{2}\Delta T \qquad \textbf{(7)}$$

The domain of the uncertain stratification parameter ξ was set to [0, 2.10^{-3}] K/W, the upper value corresponding to a maximum vertical temperature difference in the base case of 3.5 ^{o}C.

INTERNAL CONVECTIVE HEAT TRANSFER

(term 2 in (1) and term 1 in (3))

Reviews on literature reporting values and phenomenological models (correlations) for internal heat transfer coefficients from experiments can be found in Khalifa,1989, Pernot, 1989 and Halcrow, 1987.

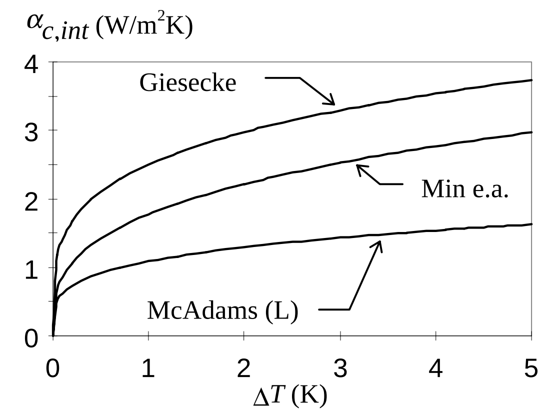

Fig. 4 The three correlations for the internal heat transfer coefficients, which were used in the sensitivity analysis.

The correlations resulting from the various experiments show a considerable spread, causing significant uncertainty in the values of the internal heat transfer coefficients. To estimate the sensitivity of the model output to this uncertainty, three sets of correlations were used: from Giesecke, 1940, Min e.a., 1956 and the laminar correlation from McAdams, 1954. Fig. 4 shows these correlations for horizontal heat flow.

The values for $\alpha_{c,int}$, reported in literature are measured over the air boundary layer at the wall. If the room air temperature is vertically stratified, the conductive heat transfer at the floor and ceiling will be:

$$\begin{aligned} q_{floor\rightarrow air} &= \alpha^{c}_{floor}\left(T_{floor} - \overline{T}_{air}\right) + \tfrac{1}{2}\alpha^{c}_{floor}\Delta T \\ q_{ceiling\rightarrow air} &= \alpha^{c}_{ceiling}\left(T_{ceiling} - \overline{T}_{air}\right) - \tfrac{1}{2}\alpha^{c}_{ceiling}\Delta T \end{aligned} \qquad \textbf{(8)}$$

These corrections are implemented in the simulation model.

SOLAR HEAT LOADS

(term 2 in (1), term 2 in (3) and term 2 in (4))

The only uncertain parameter that was considered in the modeling of the total solar irradiance on a facade, is the overall reflectance of the surroundings of the building, the albedo. In this study, concerning summer conditions, the range for the albedo is set to [0.15, 0.3].

Given the solar irradiance on the facade, the uncertainty in the internal solar loads arises from the unknown distribution of the incoming solar heat flux over the furniture (convective fraction) and the wall surfaces (radiant fraction). In the sensitivity study, the domain for the convective fraction is set to [0, 0.3].

INPUTS FROM INTERNAL HEAT SOURCES

(term 3 in (1) and term 3 in (3))

As it is assumed that the scenario only prescribes the overall internal heat load per m^2, the division between the convective and radiant part is uncertain. In the sensitivity study, the domain for the convective fraction was set to [0.5, 1.0].

EXTERNAL CONVECTIVE HEAT TRANSFER

(term 1 in (4))

Heat transfer coefficients

A review of literature on external heat transfer coefficients can be found in Strachan, Martin, 1989 and Allen, 1987.

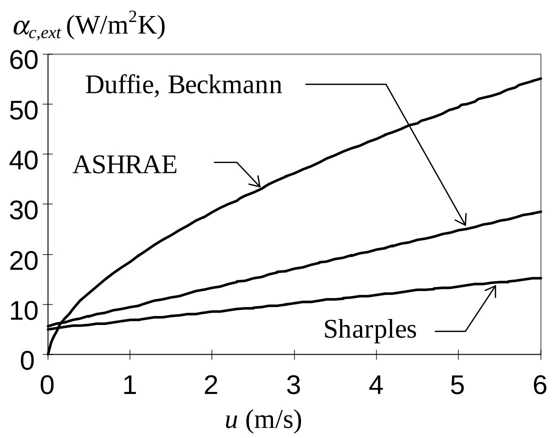

Fig. 5 The three correlations for the external convective heat transfer, which were used in the sensitivity analysis. u is the surface wind speed.

The spread in the reported values for the heat transfer coefficients is considerable. In the sensitivity study, three correlations are considered: from Sharples, 1984; Duffie and Beckmann, 1980 and ASHRAE, 1975. These are illustrated in Fig. 5.

Ambient temperature

In the local thermal field, generated by an urban area, the temperature is usually higher (heat islands) than that of its surroundings. Plate (Plate, 1995) reports maximum heat island temperatures of large cities in wintertime up to 10-12 ^oC As summer conditions in an urban area are studied here, a more conservative range for the ambient temperature in the sensitivity study is chosen: [T_{meteo} , T_{meteo} + 1] ^oC.

EXTERNAL LONGWAVE RADIANT HEAT FLUX

(terms 3 and higher in eq. (4))

In this case study, three different types of external longwave emitters were modeled: the sky, surrounding building facades and the surrounding ground. The sky radiant temperature is considered as part of the scenario specifications.

The radiant temperature of a facade of a surrounding building is assumed to be equal to the surface temperature of the facade with similar orientation in the building under study plus or minus 5^oC.

Heat conduction in the surrounding ground is modeled according to (2) with (4) as surface boundary condition and prescribed temperatures at 1.2m depth. The uncertainty in the ground surface temperature is entirely attributed to the convective heat losses at the surface. The uncertainty range [10,30] W/m^2K was used for the convective heat transfer coefficient.

THERMAL COMFORT PERFORMANCE

Since a linear thermal stratification profile in the office spaces is assumed, and the occupants reside in the lower half of the space, they will experience an average air temperature of $\overline{T}_{air} - \Delta T / 4$. This value was used in the comfort performance calculations.

NUMERICAL MODELING

The physical model, of which the principles and uncertainties were discussed in the previous sections was implemented in two separate thermal building modeling tools, ESP-r (ESRU, 1995) and BFEP (Augenbroe, 1986), a building physics finite element toolbox. With identical, base case physical modeling assumptions, the model output (thermal comfort performance) differed less than 5% between the two simulation tools, indicating that the implementation of the codes was either error-free or cursed with the same errors, and the effects of (the essentially different) numerical solvers were small.

SUMMARY OF UNCERTAIN PARAMETERS

A list of all uncertain parameters and sub-models, considered in this paper are listed in Table 2, together with a description and their ranges in the sensitivity study.

Table 2 Uncertain parameters and submodels: descriptions and ranges.

index	description	range
1	conv. heat transfer coeff. of surrounding ground (W/m^2 K)	[10, 30]
2	resistance roof air layers (m^2 K/W)	[0.17, 0.23]
3	deviation of local ambient temperature from meteo-value (^{o}C)	[0.0, 1.0]
4	deviation of radiant temperature of surrounding buildings from corresponding facade of building under study (^{o}C)	[-5.0, 5.0]
5	albedo (-)	[0.15, 0.30]
6	conv. fraction of incoming solar radiation in east office space (-)	[0.0, 0.30]
7	idem in west office space (-)	[0.0, 0.30]
8	conv. fraction of int. heat sources in east office space (-)	[0.50, 1.0]
9	conv. fraction of int. heat sources in west office space (-)	[0.50, 1.0]
10	wind reduction factor (-)	[0.50, 0.70]
11	pressure difference coefficients data set	Fig. 3
12	stratification parameter (K/W)	[0, 2.0.10^{-3}]
13	model for internal conv. heat transfer coeff.	Fig. 4
14	model for external conv. heat transfer coeff.	Fig. 5

SENSITIVITY ANALYSIS TECHNIQUE

The sensitivity analysis was carried out with the model, implemented in BFEP, as this tool offered superior possibilities to implement different sub-models and modeling assumptions.

Based on an earlier study on the suitability of different sensitivity analysis techniques for building thermal simulation models (De Wit, 1997a) it was decided to use a factorial sampling technique, developed by Morris (Morris, 1991)

In this method, the sensitivity of the model output for a parameter (alternatively referred to as the importance of a parameter) is related to a sample of independently observed *elementary effects*, changes in the output solely due to changes in a particular input. Each of the k model parameters is scaled to have a region of interest equal to [0,1]. The scaled k-dimensional parameter vector is denoted by $\boldsymbol{x}$. For each parameter, the region of interest is discretized in a grid with p levels, where each x_i may take on values from {0, 1/(p-1), 2/(p-1), ... ,1}. The elementary effect of the i-th input is defined by:

$$d_i(\boldsymbol{x}) = \left[C(x_1, \dots, x_{i-1}, x_i + \Delta, x_{i+1}, \dots, x_k) - C(\boldsymbol{x})\right] / \Delta \qquad \textbf{(9)}$$

where $x_i \leq 1\text{-}\Delta$ and Δ is a predetermined multiple of 1/(p-1). The aim of the method is to estimate the finite distribution of the $p^{k-1}[p\text{-}\Delta(p\text{-}1)]$ elementary effects associated with each input. For input i this distribution will be denoted by F_i .

A large (absolute) measure of central tendency for F_i indicates an input with an important “overall” influence on the output. A large measure of spread indicates an input whose influence is highly dependent on the values of the inputs, i.e. one involved in interactions or whose effect is nonlinear. In this paper the means and standard deviations will be used as measures for central tendency and spread respectively.

The estimates for the distributions F_i will be based on independent random samples of the elementary effects. The samples are obtained by application of carefully constructed sampling plans.

The general procedure to assess one single sample for the elementary effect of each parameter is illustrated in *Fig. 6* for a 3-dimensional parameter space.

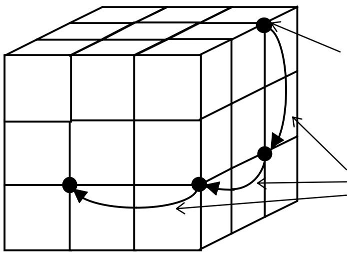

Fig. 6 Illustration of the procedure to assess one single sample for the elementary effect of each parameter. The illustration is for a 3-dimensional parameter space with a 4 level grid (k=3, p=4).

Initially, the parameter vector is assigned a random base value (on the discretized grid). An observation of the model output is made. Then a ‘path’ of k orthogonal steps through the k-dimensional parameter space is “followed”. The order of the steps is randomized. After each step an observation is made. This enables the assessment of one elementary effect per step. Subsequently, a set of r independent samples from each F_i is obtained by repeating this procedure r times.

RESULTS

In this study, the 14 parameters were discretized on a 4-level grid (p = 4) The elementary step Δ was chosen equal to 2/3, as shown in Fig. 6. The parameters, which represent sub-models or data sets (11, 13 and 14) are already discrete. However, as Fig. 3, Fig. 4 and Fig. 5 show, these can only assume 3 values. For these parameters, a 4-level grid was constructed as follows: [low, middle, middle, high], where ‘low’ means the sub-model or data set at one extreme, ‘high’ is the other extreme and ‘middle’ is the remaining one.

To obtain 5 independent samples of elementary effects for each of the 14 parameters, 75 simulation runs were required. The mean value of the thermal comfort performance C over these 75 runs was 140 hours. In

Fig. *7*, the standard deviation S_i of the elementary effects for each parameter is plotted versus their sample mean $\overline{d_i}$.

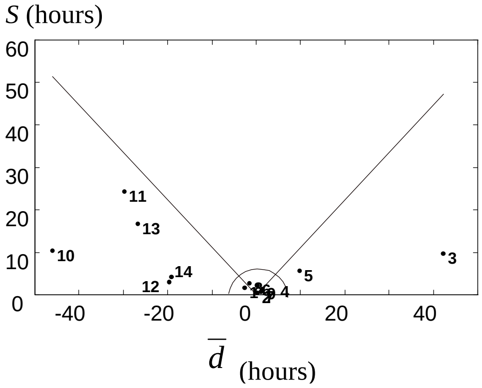

Fig. 7 Estimated means ($\overline{d}_i$) and standard deviations (S_i) of the elementary effects. The numbers in the plot are parameter indices. The solid lines correspond to $d_i = \pm 2\,SEM_i$ (SEM_i is standard deviation in sample mean $\overline{d}_i$). The arc has a radius of 7 hours, corresponding to the magnitude of the discrepancy that was found between the ESP-r and BFEP-simulations of the base-case.

The solid lines, constituting a wedge, correspond to $d_i = \pm 2\,SEM_i$, with SEM_i the standard deviation in the sample mean. If a parameter has coordinates (d_i , S_i) that lie outside the wedge, this is a strong indication that the mean elementary effect of the parameter is non-zero. A location of the parameter coordinates within the wedge indicates that interaction effects with other parameters or non-linear effects are dominant.

DISCUSSION

Two immediate conclusions can be drawn from *Fig. 7*. First, it is clear that parameters 3 (deviation of local ambient temperature from meteo-value), 10 (wind reduction factor), 11 (data set for wind pressure difference coefficients) and 13 (internal heat transfer coefficients), have the most profound effect on the thermal comfort performance *C*. Parameters 5, 12 and 14 take a second place, parameter 5 just exceeding the 5%-level of discrepancy that was observed between base case simulations with ESP-r and BFEP. These parameters represent the albedo, thermal stratification parameter and the external convective heat transfer coefficients respectively.
Secondly, none of these parameters is located within the wedge. As a result, it can be concluded that parameter interactions and non-linear effects play a minor role in this model.
The dominance of these 7 parameters leads to the expectation that they are responsible for most of the modeling uncertainty in *C*. Furthermore, a mean effect of the parameters 3 and 10 of more than 40 hours on a mean thermal comfort performance value of 140 hours indicates that uncertainty in these parameters is a matter of concern.

However, the value of the effects, found in this study, should be interpreted with care. Although based on thorough examination, the ranges that were chosen for in the sensitivity analysis are arbitrary up to some degree. For instance, the domains of the parameters 11, 13, 14, and in fact, 10, reflect the selection of alternative sub-models. The variation between alternative sub-models is a pragmatic choice, suitable for a first investigation of the sensitivities, but does not reflect the actual uncertainty.

First, the variation between these models generally conveys a variation in experimental conditions, all of which are different from the case study at hand. So, instead of assessing the uncertainty, conditional on the configuration of the case study, a variation due to alternative configurations is found.
Moreover, each sub-model or correlation found in literature, is a best fit on experimentally collected data. In other words, the information about the scatter in the experimental results is removed.

Consequently, to assess the uncertainty in the performance prediction *C* (and thereby establishing its reliability), the uncertainty, particularly in the 7 parameters mentioned earlier, needs to be thoroughly investigated. If the uncertainty in *C*, resulting from this investigation, appears to be beyond acceptable limits, a course of action can be considered to reduce these uncertainties.

For instance, the uncertainties in parameter 11 and, to a lesser degree, in parameter 10 can be reduced by wind tunnel measurements. Additionally, application of computational dynamic fluid simulations (CFD) instead of a lumped air model may diminish the uncertainty with respect to thermal stratification. However, as these measures are costly, it is imperative to get a better knowledge of the sources and magnitude of the appearing uncertainties in order to determine the surplus value of such dedicated experiments.

CONCLUSIONS

A sensitivity study was conducted to investigate the effects of modeling uncertainties on the simulation of thermal comfort performance of a naturally ventilated office building without cooling plant. The results show that 4 parameters/sub-models primarily contribute to the variability in the thermal comfort performance, i.e. the wind reduction factor, the wind pressure coefficient data set, the deviation of the local ambient temperature from the meteo-value and the choice of a model for the internal heat transfer coefficients. The effects of uncertainty in the albedo, the modeling of the external heat transfer coefficients, and the indoor thermal stratification are less striking, but still of importance. Contributions of parameter interactions and non-linear parameter effects were found to be insignificant.

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NOMENCLATURE

Most of the nomenclature is explained in the text. A few exceptions are:

ρ	density
c	specific heat
λ	conductivity
V	volume of a space