Uncertainty and sensitivity analysis of the performances of natural night ventilation

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Summary: *Natural night ventilation is an energy efficient way to improve thermal summer comfort. Coupled thermal and ventilation simulation tools predict the performances. Nevertheless, the reliability of simulation results with regard to the assumptions in the input, is still unclear. Uncertainty analysis is chosen to determine the uncertainty on the predicted performances of natural night ventilation. Sensitivity analysis defines the most important input parameters causing this uncertainty. The results for a single-sided ventilation strategy in a single office are discussed.*

Keywords: *natural night ventilation, building simulation, uncertainty analysis, sensitivity analysis*
Subject Category: *Natural and hybrid ventilation, Thermal comfort*

1 Problem definition

Natural night ventilation can be used to prevent overheating problems during summer. This passive cooling method, driven by wind and thermally (stack) generated pressures, cools down the exposed building structure at night and reduces and postpones consequently the indoor temperature peaks by day.
For a given climate, airflow rate, thermal capacity of the building and the heat, exchanged between the air and the thermal mass, define the performances of natural night ventilation. These performances are characterized by the indoor temperatures, thermal comfort and cooling capacity.

Nowadays, designers and consulting engineers can use building simulation tools to predict the performances of natural night ventilation. Two kind of building simulation models exist. Thermal simulation models calculate the indoor temperatures while ventilation network models predict the airflows. A coupled thermal and ventilation model, which iterates the mass and energy balance per zone till convergence, is necessary to simulate natural night ventilation [1].

Nevertheless, the reliability of the simulation results of these tools with regard to the assumptions, made by the user in the input, is still unclear. This uncertainty puts up a barrier for owners and designers to implement energy efficient ventilation and cooling techniques.

2 Methodology

This research aims to define on the one hand the uncertainty of the predicted performances of natural night ventilation and on the other hand the most important input parameters that cause this uncertainty.

2.1 Simulation model

The existing coupling between TRNSYS [2], a transient multizone thermal simulation model, and COMIS [3] [4], a multizone infiltration and ventilation simulation model, is chosen. Both programs subdivide the building into various zones, corresponding to the rooms. Each zone is assumed to be homogeneous and is represented by single values for air temperature and pressure. In addition, each surface has one single temperature in TRNSYS. Heat conduction between two surfaces is modeled by transfer function relationships. Besides, an artificial star network between the surface, star and air temperatures define the heat transfer by convection and radiation in a zone. The star temperature is a weighted average of the surface and air temperatures. Solving the convective energy balance in the air node and the combined convective and radiation energy balance in the star node defines these zone temperatures.

In COMIS, air flow paths connect the various zones. The air flow through vertical large openings for example (e.g. windows and doors) is calculated as a two-directional gravitational air flow. The mass flow is calculated for both directions at several levels within the opening by the orifice equation and summed up to obtain the total flow for the whole opening. Closed large openings, fans out of action and air leaks are represented by the power law equation [5]. Solving this steady state system of non linear equations by using mass conservation, defines the pressure in each zone and the air flow through every link.

2.2 Performances: thermal comfort

Thermal summer comfort, achieved by natural night ventilation, is characterized by the sum of weighted temperature exceeding hours (GTO) [6] during occupation time. Determination of GTO is based on the comfort theory of Fanger [7]. Thermal discomfort occurs each time the predicted mean vote (PMV) exceeds 0.5 (the predicted percentage of dissatisfied people (PPD) exceeds 10%). The indoor temperature, corresponding to this threshold, varies with indoor environmental parameters (air velocity, relative humidity) and personal properties (metabolism, activity level and clothing). Weighted temperature exceeding hour (WF) takes into account the degree of exceeding. WF is directly proportional to the increase of the PPD: an hour with 20% dissatisfied people counts twice as an hour with 10% dissatisfied.

$$WF = 0.47 + 0.22.|PMV| + 1.30.|PMV|^2 + 0.97.|PMV|^3 - 0.39.|PMV|^4 \quad (1)$$

A good internal thermal comfort is characterized by a GTO smaller than 150 [8]. This value corresponds to an average of 15% dissatisfied people during 5% of annual occupation time.

2.3 Uncertainty analysis

To analyse the uncertainty on the thermal comfort, given the uncertainty on the input parameters, Monte Carlo analysis (MCA) [9] is chosen. MCA performs multiple evaluations with randomly selected model input parameters and involves the following steps: selection of ranges and distributions for each input parameter characterizing uncertainty, generation of a sample of input parameters from the selected distributions, evaluation of the model for each element of the sample, uncertainty analysis.

Latin Hypercube sampling (LHS) is used to build a N*k sample with N elements of k input parameters. LHS ensures full coverage of the range of each input parameter. The range of each variable is divided into N non-overlapping intervals of equal probability 1/N. One value from each interval is at random selected. These N values of the first input factor are step-by-step and at random combined with N randomly chosen values of each other input factor. Minimum number of evaluations of the model required for Latin Hypercube sampling, i.e. minimum elements of a representative sample, is one and a half times the number of input factors [10].

2.4 Sensitivity analysis

Sensitivity analysis is a method to study, qualitatively or quantitatively, how the variation in the output of a model is attributed to different sources of variation [9], i.e. boundary conditions, building properties and model assumptions.

The impact of these factors on the predicted performances of natural night ventilation is in this research examined by a screening method. Factor screening identifies and ranks the most influential parameters. The One-at-a-time design of Morris [11] is chosen. This method calculates the main impact of each factor. A number (r = 4 to 10) of elementary effects of each parameter are calculated at different points in the input space. An elementary effect of a parameter is the influence of a local variation of this parameter on the result. The input vector **x** consists of k input factors x_i varying between $[x_{i,min}, x_{i,max}]$ and having p values in the set:

$$x_{i,min} + \Delta x \left\{0, \frac{1}{p-1}, \frac{2}{p-1}, \ldots, 1\right\} \quad (2)$$
$$\Delta x = x_{i,max} - x_{i,min}$$

Let Δ be a predetermined multiple of 1/(p-1) and equal for all input parameters. Then Morris defines an elementary effect of the ith factor at a given point **x** as:

$$d_i(\mathbf{x}) = \frac{[y(x_1,\ldots,x_{i-1},x_i+\Delta,x_{i+1},\ldots,x_k) - y(\mathbf{x})]}{\Delta} \quad (3)$$

The points **x** in the parameter space are chosen such that each factor is varied over its whole variation interval.
The mean and the standard deviation of these elementary effects determine the impact of the factor on the output. A high mean indicates a factor with an important overall influence on the output, a high standard deviation indicates a factor interacting with other factors or a factor whose effect is non linear.

Morris proposed an economical design for the input matrix. The successive vectors $\mathbf{x}^{(1)}$, $\mathbf{x}^{(2)}$, …, $\mathbf{x}^{(k+1)}$ only differ in one factor, are randomly determined and define a trajectory in the parameter space. Total number of simulations equals (k+1) * r, i.e. the number of factors + 1, multiplied by the number of elementary effects.

Monte Carlo Analysis [9] is chosen to verify the set of parameters, identified as most influential in the factor screening of Morris, causing the majority of the uncertainty in the model output. Therefore the variances on the output, resulting from three input samples, are compared [12]:

- All factors are varied
- Identical to the first sample for influential factors, mean values for other parameters
- Mean values for influential factors, identical to the first sample for other parameters.

3 Results

3.1 Model

Natural night ventilation by single-sided ventilation in a single office is studied. Figure 1 shows a two-zone model (office and part of the corridor), based on a single office on the first floor at the west side of the

PROBE building (Limelette, Belgium) [13]. Internal separations are assumed to be adiabatic.

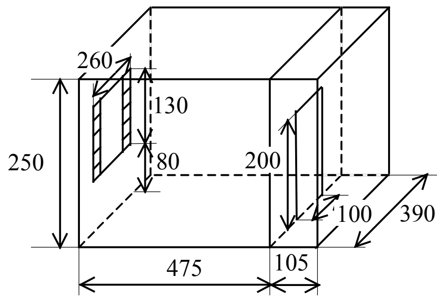

Fig. 1. A 2-zone model of a single office on the first floor at the west side of PROBE building (Limelette, Belgium).

All 69 input parameters are normally distributed. The given ranges correspond to $[\mu-2\sigma;\mu+2\sigma]$. This means a parameter is included in this interval with a probability of 0.98.

The uncertainty interval of all dimensions equals the average value ± 0.02 [12]. Mean wall properties are given in Table 1. The uncertainty of material properties is caused by variations in temperature and humidity and shown in Table 2 [14]. Internal heat gains vary from 8.4 to 24.3 W/m² in the office and are 4.4 W/m² in the corridor. Sunblinds are lowered from an irradiation of [180;220] W/m². Table 3 shows the uncertainty intervals of the internal convective heat transfer coefficients. Equation 4 defines the external convective heat transfer coefficient as a function of the local wind velocity v [15]:

$$\alpha_{ce} = 5.6 + 3.9\,v \tag{4}$$

Equation 5 [16] calculates this wind velocity on site at building height from the wind velocity at the meteo station $\overline{v}_{ref}$ with z_{bound} the boundary height and a_0 and a_m the roughness parameters respectively on site and at the meteorological station (see Table 4).

$$\overline{v}_z = \overline{v}_{ref}\left(\frac{z}{z_{bound}}\right)^{a_0}\left(\frac{z_{bound}}{10}\right)^{a_m} \tag{5}$$

Fig. 2 shows the average wind surface pressure coefficients Cp. The uncertainty interval for the façade and flat roof equal respectively the mean value ± 0.15 and ± 0.2. Table 5 describes the characteristics of the natural ventilation openings.

During occupation time, ventilation is supplied in the office at a rate of 22.5 to 27.5 m³/h.pers and partly mechanically extracted in the corridor. The temperature of the supply air equals the outdoor temperature. Natural night ventilation is only possible during nights between successive working days from 17h till 8u. The operation depends on the maximum inside and outside air temperature during the last day ($\theta_{i,a,max}$ > [21;25] °C and $\theta_{e,a,max}$ > [18;20] °C).

To define the thermal comfort (GTO), an air velocity of 0.1 m/s, a metabolism of 70W/m² and a clothing resistance of 0.7clo are assumed [17]. Equation 6 calculates the internal vapour pressure [18]:

$$\begin{aligned} p_i &= \overline{p}_i + \hat{p}_i \cos\left(2\pi\left(t-210\right)/365.25\right) \\ \overline{p}_i &= 1370\,\text{Pa}, \hat{p}_i = 220\,\text{Pa and } t = \text{day of year} \end{aligned} \tag{6}$$

Simulations are carried out from May 15 till September 30. External climatic data from the test reference year (TRY) Uccle (Belgium) are used. The difference between the local outdoor temperature and the temperature from the TRY is included in the interval [-1;1] °C. The time step is 1h.

Table 1. Wall properties: composition and U-value.

wall	*composition*	*U (W/m²K)*
floor	Reinforced concrete	1.95
External wall	Brick cavity wall	1.58
roof	Reinforced concrete - 11.5 cm insulation	0.33
Internal wall offices	Gypsum board + 5cm insulation	0.56
internal wall office-corridor	Brick wall	2.97
window	Glass + Aluminum frame g_{glass}=[0.58;0.60] $g_{glass+sunblinds}$ = [0.10;0.20] A_{frame} = [0.2;0.3]%	1.79

Table 2. Material properties: mean (μ) and standard deviation (σ) of conduction (λ), density (ρ), solar absorption (a) and specific heat (c) [14].

material		*λ (W/mK)*	*ρ (kg/m³)*	*a (-)*	*c (J/kgK)*
Façade brick	μ	0.789	1720	0.49	837
	σ	0.077	25	0.04	90
Internal brick	μ	0.54	1200	0.49	839
	σ	0.055	21	0.04	90
Reinforced concrete	μ	1.680	2310	0.68	840
	σ	0.162	38	0.04	90
Light concrete	μ	0.313	891	0.68	839
	σ	0.03	15	0.04	90
bitumen	μ	0.237	1188	0.9	1135
	σ	0.012	4	0.04	46
insulation	μ	0.039	38	-	1072
	σ	0.003	3	-	57
Gypsum board	μ	0.28	950	0.40	882
	σ	0.028	17	0.03	70
Air cavity	μ	0.18	-	-	-
	σ	0.015	-	-	-

Table 3. Internal convective heat transfer coefficients [15], [19] and [20].

α_{ci} *(W/m²K)*	*By day*	*At night*
floor	Stably stratified [0.2;0.64]	Buoyant [1;3.2]
roof	Buoyant [1;3.2]	Stably stratified [0.2;0.64]
vertical	Natural convection [1;3.2]	Natural convection [1;3.2]

Table 4. Roughness parameter a and boundary height z_{bound} at meteo station and on site [16].

location	*Terrain description*	z_{bound} *(m)*	*a (-)*
Meteo station	open country with low scrub and scattered trees	60	[0.147;0.151]
On site	roughly open	60	[0.177;0.187]

Table 5. Natural ventilation opening properties [21].

opening	*A (m²)*	C_D *(-)*	*C (kg/s.m.Pa)*	*n (-)*
louvre	[0.39;0.45]	[0.31;0.47]	[0;0.0021]	0.6
Int. door	[1.94;2.06]	[0.6;0.9]	[0.0008;0.0024]	0.6

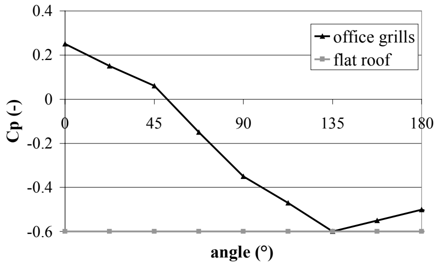

Fig. 2. The wind surface pressure coefficient Cp depends on the angle between the wind direction and the normal on the surface [21].

3.2 Uncertainty analysis

Simlab [10], software developed for uncertainty and sensitivity analysis, is used to prepare 500 independent Latin Hypercube samples. This number exceeds largely the minimum number of 3/2 * 69 factors = 104. Fig. 3 shows the result of the uncertainty analysis. A good internal thermal comfort (GTO < 150) in a west office of PROBE with natural single-sided night ventilation occurs with a probability of 0.72

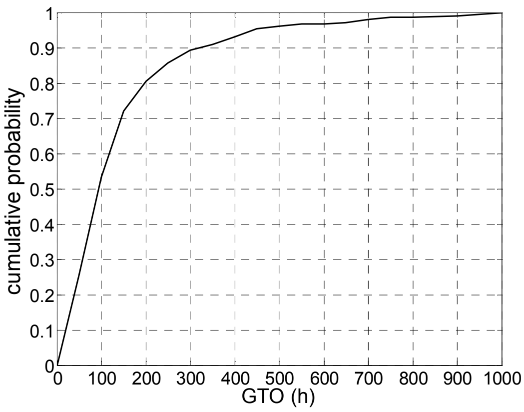

Fig. 3. Cumulative probability of the thermal comfort (GTO) of natural night ventilation by single-sided ventilation.

3.3 Sensitivity analysis

Fig. 4 and Fig. 5 (zoomed in) show the results of the sensitivity analysis by Morris. 10 independent trajectories are considered. The mean and standard deviation of the elementary effects per factor on the thermal summer comfort are calculated. The sign of the elementary effect of various factors differs. A positive sign proves increasing this parameter causes an increase of GTO and thus a decrease of thermal comfort. The standard deviation has mostly a large value ($\sigma \approx \frac{\mu\sqrt{r}}{2}$, i.e. dotted V-curve on the figures below). This means most factors have a non-linear effect or interact with other factors.

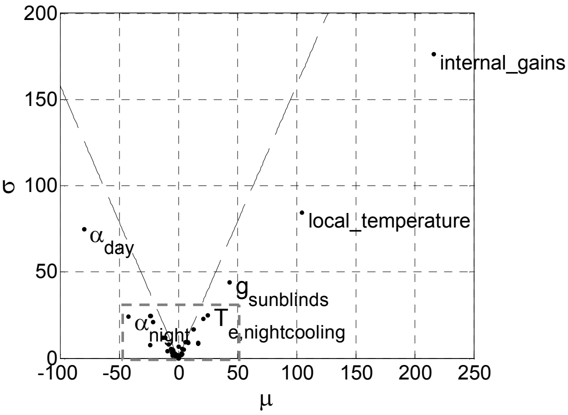

Fig. 4. Estimated mean (μ) and standard deviation (σ) of the elementary effects of input factors on thermal comfort.

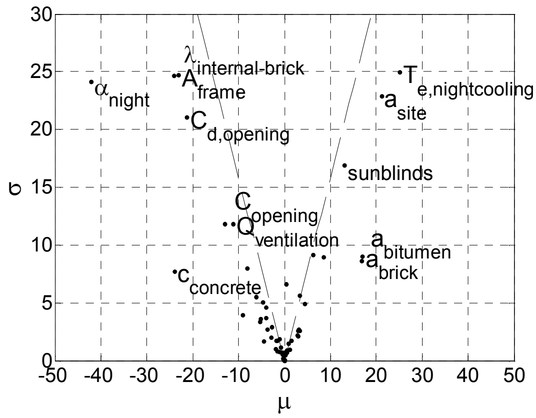

Fig. 5. Estimated mean (μ) and standard deviation (σ) of the elementary effects (zoomed in).

Most influential parameters on the thermal comfort in a single-sided night ventilated office are summarized in Table 6. Following groups of parameters can be distinguished:

- influencing internal and solar heat gains: internal heat gains, properties of sunblinds, external solar absorption roof and façade
- determining conduction and ventilation heat losses: local outdoor temperature, thermal conduction façade, external convective heat transfer, infiltration and mechanical ventilation.
- defining night ventilation: internal convective heat transfer by day and night, control, heat storage capacity, opening properties.

Internal heat gains, local outdoor temperature and internal heat transfer by day are noticed to have largely the greatest impact on thermal comfort. Moreover, similar parameters can have a different impact. The influence of the convective heat transfer by day for example is twice the influence of the convective heat transfer by night as the coefficient by day has a direct impact on the indoor temperature. Concerning the control parameters for night ventilation, the impact of the maximum outdoor air temperature during the last day ($T_{e,nightcooling}$) is much larger than the impact of the maximum indoor air temperature during the last day ($T_{i,nightcooling}$). Contrary to the outdoor temperature, the threshold for the internal temperature is always exceeded on warm summer days. As a result, the corresponding control parameter influences little the thermal comfort.

Table 6. Most influential parameters on the uncertainty of thermal comfort.

index	***description***	***µ***
internal_gains	Internal heat gains	216
local_ temperature	Local outdoor temperature	105
α_{day}	Internal heat transfer by day	-80
α_{night}	Internal heat transfer by night	43
$g_{sunblinds}$	Solar transmission of sunblinds	-42
$T_{e,nightcooling}$	Controlling night ventilation	25
$\lambda_{internal\text{-}brick}$	Thermal conduction internal wall	-24
$c_{concrete}$	Heat storage capacity	-24
A_{frame}	Surface window frame	-23
a_{site}	Roughness on site, defines external convective heat transfer (see equations 4 and 5)	21
$C_{d,opening}$	Natural night ventilation opening property	-21
$a_{bitumen}$, a_{brick}	External solar absorption	17
sunblinds	Controlling sunblinds	13
$C_{opening}$, $Q_{ventilation}$	Infiltration and mechanical ventilation	-13

Table 7. Validation of sensitivity analysis.

Variance (% of total)	***Most influential factors varied***	***All factors except most influential varied***	***Rest fraction***
Table 6	94	0.3	5.7
Top 3	62	2	36
Top 2	55	4.5	40.5

Table 7 proves the factors from Table 6, identified as the most influential in the sensitivity analysis, have the greatest impact on the thermal comfort. These factors together cause 94 % of the total variance. The other factors together are responsible for 0.3 % of the total uncertainty. 5.7 % is left for interactions between these two groups of parameters.

This rest fraction becomes very large considering only the internal heat gains, local outdoor temperature and internal convective heat transfer coefficient by day as most influential factors (top 3 in Table 7). This means the factors of Table 6 have only an important impact on the thermal comfort interacting with the internal heat gains, local outdoor temperature and internal convective heat transfer coefficient by day. This conclusion is confirmed by varying only the internal heat gains and local outdoor temperature (top 2 in Table 7).

3.4 Impact of thermal mass

The considered office in the PROBE building has a high thermal mass. The impact of this on the results of the uncertainty and sensitivity analysis is discussed in this section.

Fig. 6 compares the cumulative probability of the thermal comfort of an office with high, medium (false floor) and low thermal mass (false floor and ceiling). Thermal comfort in the office with a false floor is similar to the office with high thermal mass. Probability of a good thermal comfort decreases in the office with false floor and ceiling (p = 0.41).

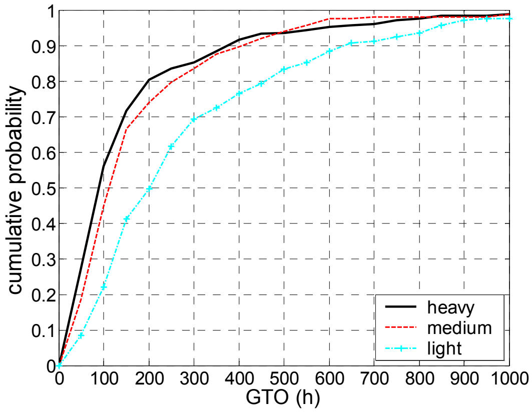

Fig. 6. Impact of thermal mass on the cumulative probability of thermal comfort (GTO) of natural night ventilation by single-sided ventilation.

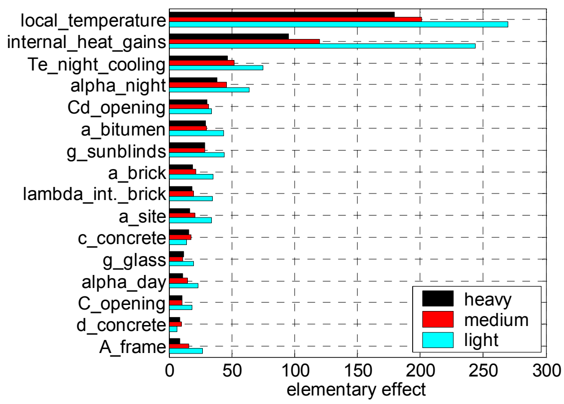

Fig. 7. Impact of thermal mass on most influential parameters on thermal comfort, identified by one-at-a-time method of Morris.

Fig. 7 shows the impact of thermal mass on the sensitivity analysis. The most influential parameters of the 'medium' office hardly differ from the 'heavy' office. Following differences are noticed between the 'light' and 'heavy' office. Impact of some properties of natural night ventilation ($C_{d,opening}$ and $c_{concrete}$) reduces. Thermal comfort is, on the contrary, more sensitive to properties defining solar and internal heat gains ($g_{sunblinds}$, A_{frame}, internal_gains). The influence of the resistance of the air cavity (not shown on Fig. 7) increases as this layer defines the (extremely) limited heat storage of false floor and ceiling.

4 Conclusion

Uncertainty analysis is used to investigate the uncertainty of the predicted thermal comfort in an office, cooled with natural single-sided night ventilation. In the considered single office with high thermal mass, good internal comfort occurs with a probability of 0.72.

Sensitivity analysis defines the most important input parameters causing this uncertainty. Internal heat gains, local outdoor temperature and internal convective heat transfer coefficient by day have largely the most important impact on thermal comfort in this case. All the other factors have only an important impact on thermal comfort interacting with internal heat gains, local outdoor temperature and internal convective heat transfer coefficient by day.

The impact of thermal mass on the results of the uncertainty and sensitivity analysis is discussed. These results are comparable in an office with high or medium thermal mass. Probability of a good thermal comfort decreases nearly 50% in an office with false floor and ceiling. The thermal comfort is in that case less sensitive to properties of natural night ventilation and more sensitive to properties defining heat gains.

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