UNCERTAINTY AND SENSITIVITY ANALYSIS TO EVALUATE NATURAL NIGHT VENTILATION DESIGN IN AN OFFICE BUILDING

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ABSTRACT

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 the 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. In addition, sensitivity analysis defines the most important input parameters causing this uncertainty. This methodology is used to evaluate one of the possible design schemes of natural night ventilation in a new office building of the Ghent University (Belgium).

KEYWORDS

Natural night ventilation, TRNSYS - COMIS, uncertainty and sensitivity analysis.

INTRODUCTION

Natural night ventilation is an interesting passive cooling method. Driven by wind and thermally (stack) generated pressures, natural night ventilation cools down the exposed building structure at night, in which the heat of the previous day is accumulated. Temperature peaks are consequently reduced and postponed. Designers utilize building simulation to predict the performances of natural night ventilation. Nevertheless, the reliability of these simulation results with regard to the assumptions, made by the user in the input, is still unclear. This uncertainty puts up a barrier to implement energy efficient cooling techniques. Therefore, this research aims to define the uncertainty of the predicted performances of natural night ventilation as well as the input parameters causing this uncertainty. This methodology is used to evaluate one of the possible design schemes of natural night ventilation in a new office building of the Ghent University (Belgium).

METHODOLOGY

The thermal comfort achieved by natural night ventilation is characterised by the weighted excess hours during occupation time (GTO). Determination of GTO is based on the comfort theory of Fanger (Fanger, 1972), which takes both indoor environmental parameters (air and radiant temperature, air velocity and relative humidity) and personal properties (metabolism, activity level and clothing) into account. The hourly weight factor (WF) takes the degree of discomfort in consideration and is directly proportional to the increase of the predicted percentage of dissatisfied people (PPD): one hour with 20 % dissatisfied people is equal to two hours with 10 % dissatisfied. A PMV of 0.5 corresponds to a WF of 1 (see Eqn. 1).

$$\text{if PMV} < 0.5 \text{ then } WF = 0 \text{ else } WF = 10 - 9.5 \exp\left[-\left(0.03353 \text{ PMV}^4 + 0.2179 \text{ PMV}^2\right)\right] \quad (1)$$

A number of weighted working hours in which more than 10 % of the occupants are dissatisfied (predicted mean vote or PMV > 0.5) less than 150 - 200 h, means a good thermal summer comfort (van der Linden et al., 2002).

A coupled thermal and ventilation model, which iterates the mass and energy balance per zone till convergence, is necessary to simulate natural night ventilation (Breesch and Janssens, 2002) as the internal temperatures depend on the ventilation flow rates. Because natural night ventilation is temperature driven, the flow rate is on its turn function of the indoor air temperatures. The existing coupling between TRNSYS 16 (SEL et al., 2004), a transient multizone thermal simulation model, and COMIS 3.1 (Dorer et al., 2001), a multizone infiltration and ventilation simulation model, is chosen to predict the performances of natural night ventilation. Both simulation programs subdivide the building in various zones, mostly corresponding to the rooms, in which the air is assumed to be perfectly mixed.

To analyse the uncertainty on the predicted thermal comfort, given the uncertainty on the input factors, Monte Carlo analysis (MCA) (Saltelli et al., 2000) is chosen. MCA performs multiple evaluations with randomly selected model input parameters. The following steps are successively carried out: selection of a range and distribution for each input parameter, sample generation from these distributions, evaluation of the model for each element of this sample and uncertainty analysis. Latin Hypercube sampling (LHS) is chosen to build a N*k sample with N elements of k input parameters because LHS ensures better coverage of the range of each input parameter than random sampling. The range of each variable is divided into N non-overlapping intervals of equal probability 1/N. One value from each interval is randomly 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. The minimum number of model evaluations, required for Latin Hypercube sampling for a representative sample, is one and a half times the number of input factors (POLIS, JRC-ISIS, 2003).

Furthermore, sensitivity analysis studies how the variation in the thermal comfort is attributed to the variation in the input parameters. Global sensitivity, based on MCA, incorporates the influence of the whole range of variation and distribution of each input parameter and evaluates the effect of one parameter while all other parameters are varied as well. The standardized rank regression coefficient (SRRC) ranks and quantifies the effect of the input factors on the thermal comfort and are deduced from linear regression analysis on rank-transformed input data. Eqn. 2 defines the standardized linear regression model from a N*k sample with N elements of k input factors (with j = 1,2,…,k; i = 1,2, …,N; x = input; y = output; b_j = regression coefficient):

$$\frac{y-\bar{y}}{\hat{s}} = \sum_{j=1}^{k} \frac{b_j \hat{s}_j}{\hat{s}} \frac{\left(x_j - \bar{x}_j\right)}{\hat{s}_j}$$

$$\text{with } \bar{y} = \sum_{i=1}^{N} \frac{y_i}{N},\ \bar{x}_j = \sum_{i=1}^{N} \frac{x_{ij}}{N}\quad \hat{s} = \left[\sum_{i=1}^{N} \frac{\left(y_j - \bar{y}\right)^2}{N-1}\right]^{1/2}, \hat{s}_j = \left[\sum_{i=1}^{N} \frac{\left(x_{ij} - \bar{x}_j\right)^2}{N-1}\right]^{1/2} \quad (2)$$

The coefficients $\frac{b_j \hat{s}_j}{\hat{s}}$ are called SRRCs. Assuming the input factors x_j independent, SRRC estimates the importance of an input x_j while all other input factors remain their expected value. Both the distribution of the input x_j and its impact on the output affect the SRRC.

CASE STUDY

One of the possible design schemes of natural night ventilation by thermal stack in a new office building of the Ghent University (Belgium) is studied. The examined building, situated on the west side of a courtyard, consists of three office floors on top of a foyer and two underground service floors and is part of large complex of offices, laboratories and an auditorium in the city centre of Ghent. The office floors have a an area of 24.7 x 11 m², the height between floor and false ceiling and two floors respectively is 2.9m and 3.9m, the total height is 18m. The curtain wall façade of the offices is composed of sandwich (63%) and glass (37%) panels, the stairwell is completely finished with glass. Figure 1 shows the operation scheme of the natural ventilation (by day and night) on a floor plan and a cross section. Outside air enters the offices on each floor through top hung windows, cools down the exposed floor by night, flows through the false ceiling to the corridor and continues its way to the central stairwell on the south side of the courtyard where the air leaves the building at the top through outlet windows on both sides.

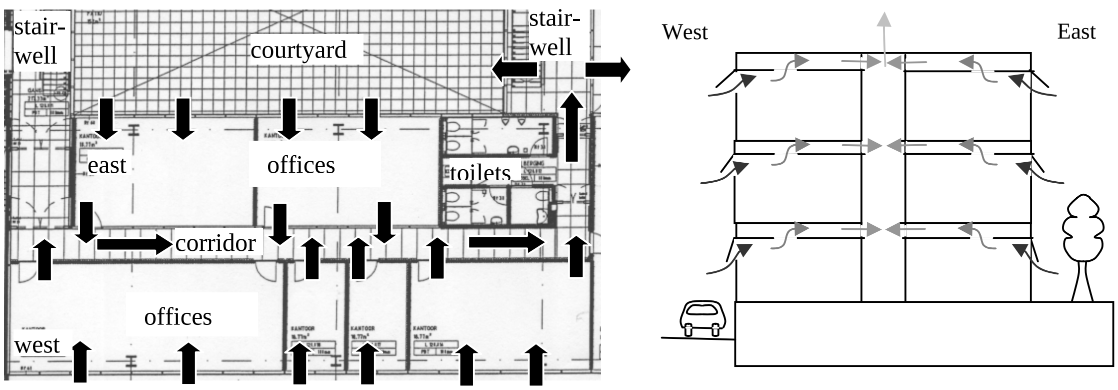

Figure 1: Operation scheme of natural ventilation on a floor plan (left) and on a cross section (right)

The simulation model simplifies the building geometry and includes on each floor one office on the west and the east side, connected by a circulation zone, i.e. the corridors and the stairwell. All the input parameters are assumed to be normally distributed. The distributions are estimated from data in the literature and standards. The given ranges correspond to $[\mu - 2\sigma; \mu + 2\sigma]$, with μ and σ respectively the mean and standard deviation.

Hourly design weather data in Uccle (Belgium) are calculated by Meteonorm (Meteotest, 2003), based on monthly average measured data from 1961-1990. Simulations are carried out from May 21 to September 15. The internal heat gains vary from 25 to 35 W/m² in the offices, 3 W/m² in the corridor. Wall compositions and material properties (BIN, 2001) are shown in table 1. Uncertainties on these values are caused by temperature and humidity variations and are calculated according to (ISO, 1999), taking into account a temperature difference of 10°C and a humidity ratio depending on kind of the material (CEN, 2000). Solar absorption coefficients are taken from (Clarke et al., 1990). The transmittance coefficient U of glass is not varied: 1.1 W/m²K, the solar transmission coefficient varies from 0.58 to 0.62. External sunblinds are provided on all windows and are automatically controlled to be lowered from an irradiation of [135;165] W/m² and have a g-value (glass included) from 0.1 to 0.2. The convective heat transfer coefficient on external surfaces depends on the local wind velocity on site (ASHRAE, 2001). In addition, the internal convective heat transfer coefficient by natural convection is function of the temperature difference between the surface and the air as shown in table 1. A time step of 15 min is chosen. Internal separations between the concerned office and the rest of the building are assumed to be adiabatic. The offices are assumed to be occupied from Monday to Friday from 9h to 18h.

The wind velocity on site is calculated from the meteorological wind velocity taking the roughness height z_0 on site and at the meteo station into account (table 1). Figure 2 shows the wind pressure coefficients Cp influenced by the enclosed buildings, calculated with the Cp generator of Knoll et al. (1995). The air tightness of the façade is characterised by an air mass flow coefficient C from 6 to $14*10^{-5}$ kg/(s.Pa^n.m²) (Tamura and Chia, 1976) and modelled by cracks on office floor and ceiling height. The night ventilation openings in the façade are automatically controlled in each office separately (table 1). This table also defines the effective leakage area (ELA) of the openings at night in 1 office module of 2.6m wide on each floor, with a discharge coefficient C_D from 0.4 to 0.8 (Flourentzou et al., 1998). The ELA of the exhaust openings in the stairwell is 4.6m². The natural ventilation openings by day are controlled to let pass an air flow of 1 or 3 vol/h when the indoor temperature exceeds 22°C.

TABLE 1
Building data

wall	**composition**
External wall	Sandwich + 9 cm insulation
Roof	False ceiling + reinforced concrete + 12 cm insulation
Internal wall	Gypsum board + 5cm insulation
Intermediate floor	False ceiling + reinforced concrete

Material properties		**λ (W/mK)**	**ρ (kg/m³)**	**a (-)**	**c (J/kgK)**
Aluminium	μ	203	2700	0.53	880
	σ	0	27	0.06	0
Reinforced concrete	μ	1.70	2400	0.72	1000
	σ	0.11	24	0.04	38
Light concrete	μ	0.24	850	0.72	1000
	σ	0.02	9	0.04	84
bitumen	μ	0.23	1100	0.88	1700
	σ	0	0	0.01	0
insulation	μ	0.040	50	-	840
	σ	0.001	0	-	10
Gypsum board	μ	0.25	900	0.40	1050
	σ	0.02	9	0.05	86
Air cavity: R (mK/W)	μ	0.16	-	-	-
	σ	0.01	-	-	-

Internal convective heat transfer coefficient

$$\alpha_{ci} = C\left(\Delta\theta\right)^n$$

	vertical	**horizontal**	
		Buoyant	**Stably stratified**
C	[1.31; 2.30]	[1.52; 2.27]	[0.29; 0.6]
n	[0.33; 0.24]	[0.33; 0.24]	[0.13; 0.25]

Operation natural night ventilation
Previous day
$\theta_{i,max}$ > [22.5; 23.5]°C
At that moment
22h < time < 6h θ_i > [18.5; 19.5]°C θ_i - θ_e > [1.5; 2.5]°C θ_e > [9.5; 10.5]°C

Characteristics of night ventilation openings in 1 office module		
floor	**ELA supply (m²)**	**ELA circulation (m²)**
first	0.08	0.16
second	0.10	0.17
third	0.24	0.18

location	**Terrain description**	**z_0 (-)**
Meteo station	Cultivated open fields	[0.03;0.05]
On site	Mean city centre	[1;4]

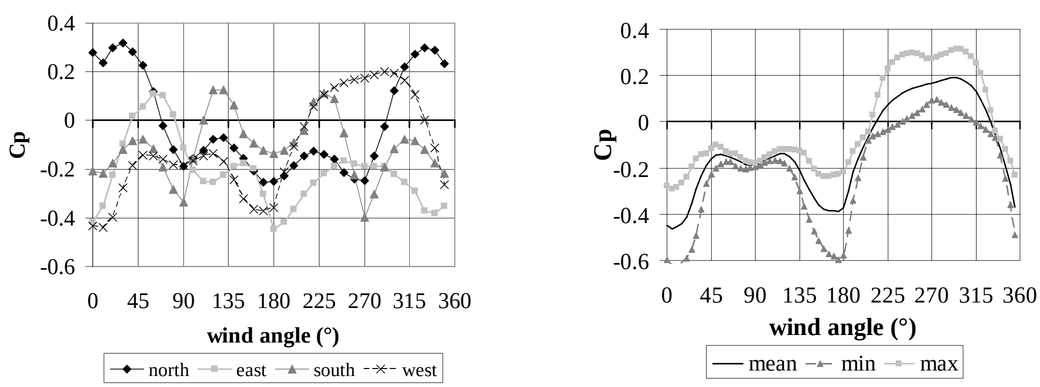

Figure 2: mean wind pressure coefficients Cp (left) and variation on Cp on the west side (right)

DISCUSSION

The thermal summer comfort in the new office building of the Ghent University (Belgium) is studied by uncertainty and sensitivity analysis. 100 independent Latin Hypercube samples (> minimum = 92 = 1.5 x 61 factors) are developed using Simlab software (POLIS, JRC-ISIS, 2003). Figure 3 (left) shows the results of the uncertainty analysis. On none of the floors a good comfort level is noticed. The probability of a reasonable comfort is higher in an office on the west than on the east side on the same floor because west winds are more frequent in Belgium and the east side of the building is more shielded against the wind. As a consequence, cross ventilation happens by night and day, causing more cooling in the offices on the west side. Furthermore, poor thermal comfort has a higher probability as the floor level rises due to smaller thermal stack height. On the 3rd level, the air is even most of the time flowing out instead of into the supply openings because the neutral pressure plane is underneath these supply openings because the height difference between the supply on the 3rd level and the exhaust in the stairwell is too small. This is shown in figure 3 (right) which compares the internal temperatures and air flows between the 2nd and 3rd level on the east side. The air flow rates flowing into the 3rd level from outside are much smaller than into the 2nd level.

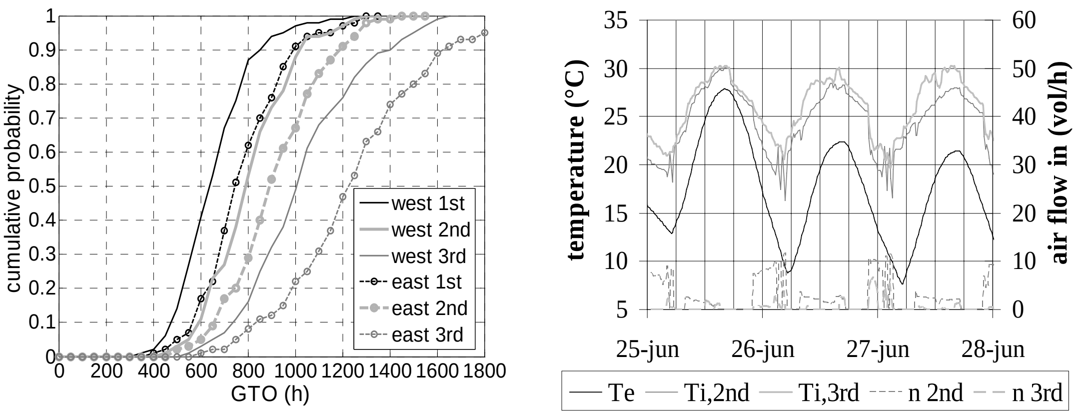

Figure 3: distribution of thermal comfort GTO (left) and comparison of temperatures and flows on the 2nd and 3rd floor on the east side in the building with mean properties (right)

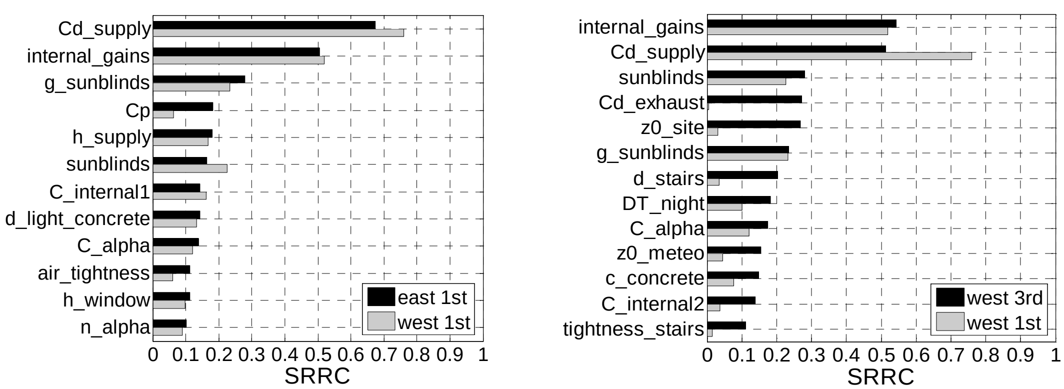

Figure 4: Most influential input parameters on thermal comfort in an office on the west and east side (left) and on the 1st and the 3rd floor on the west side compared (right)

Sensitivity analysis, characterized by SRRC, defines the impact of all input parameters on the thermal comfort, defined by GTO (figure 4). In all offices, the discharge coefficient Cd of the supply openings, the internal heat gains and the characteristics of the sunblinds have the greatest impact on the thermal comfort. At a later stage, input parameters defining the heat transfer and storage (C_alpha, n_alpha, d_light_concrete, c_concrete), the flow resistance of the circulation (C_internal) and controlling natural night ventilation (DT_night, Ti,min-night) are important. Most influential input factors are the same on the first 2 floors. Although, differences exist between the offices on the west and the east side as shown in figure 4 (left). The wind pressure coefficient Cp and the air tightness of the façade have much more impact on the thermal comfort in the east office. This means the effect of the wind on the ventilation is higher on the east side (see above). Differences are also noticed between an office on the 1st and the 3rd level (see figure 4 (right) for 2 west offices). Generally, the absolute impact of the input parameters on the thermal comfort is higher on the 3rd than on the 1st level. In addition, the impact of the characteristics of the stairs (Cd_exhaust, d_stairs, tightness_stairs) and other offices (C_internal2, air_tightness_west) on the comfort on the 3rd level is striking as well as the impact of parameters influencing the wind velocity (z0_site, z0_meteo). The air flowing out the supply openings on the 3rd floor due to thermal stack explains these conclusions.

CONCLUSION

Uncertainty and sensitivity analysis are used to evaluate one of the possible design schemes of natural night ventilation in a new office building of the Ghent University (Belgium). On none of the floors, a good comfort level is noticed. The probability of poor comfort is larger on the east side and on a higher floor. The discharge coefficient of the supply openings, the internal heat gains and the characteristics of the sunblinds have the greatest impact on the thermal comfort. In the offices on the east side, the wind has also a high influence on the thermal comfort. On the 3rd level, the impact of the design of the stairwell and other offices and of input parameters influencing the wind velocity, is striking.

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