BUILDING SIMULATION TO PREDICT THE PERFORMANCES OF NATURAL NIGHT VENTILATION: UNCERTAINTY AND SENSITIVITY ANALYSIS

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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. Sensitivity analysis defines the most important input parameters causing this uncertainty. The results for a single-sided and cross ventilation strategy in a single office are discussed and compared.

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. As a consequence, temperature peaks will be reduced and postponed. A maximum decrease of the peak temperatures of 2-4 °C has been noticed in office buildings (Kolokotroni, 1995; Martin and Fletcher, 1996; Geros et al., 1999; Blondeau et al., 1997; Pfafferott et al., 2003). This performance depends on the ventilation rate by night, the accessible thermal mass of the building, the convective heat transfer between the ventilation air and the thermal mass, the temperature difference inside-outside and the control strategy. In addition, climatic conditions and heat gains restrict the application of natural night ventilation. Firstly, only hot and moderate climates with a diurnal temperature difference of minimum 10-12°C are suited (Givoni, 1994; Kolokotroni, 1995). Secondly, natural night ventilation may only satisfy a low or moderate cooling demand. A maximum of 20-30 W/m² is recommended in heavy constructions by (IEA Annex 28, 1997; van Paassen et al., 1998).

Natural night ventilation has been gradually introduced in office buildings in Belgium during the last years (Heijmans and Wouters, 2000; Breesch et al., 2004; 2005). Designers utilize building simulation at this to predict the performances of this passive cooling technique. 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 that cause this uncertainty. This paper will discuss and compare the results for a single office with single-sided and cross ventilation stategy at night.

METHODOLOGY

Thermal comfort

The performances of natural night ventilation are characterised by the adaptive thermal summer comfort (Brager and de Dear, 2000; de Dear and Brager, 2002). Comfort measurements in naturally ventilated buildings, where occupants are able to open windows and adjust indoor conditions, revealed a strong relation between the preferred indoor temperature and the prevailing external temperature. This is caused by behavioural and psychological thermal adaptation. Behavioural adaptation refers to any conscious or unconscious action a person might make to alter their body's thermal balance, including changing clothes, opening windows, etc. Psychological adaptation on the other hand means that the perception of thermal conditions depends on past experiences and expectations.

Based on this adaptive comfort theory of Brager and de Dear, the ATG method (Dutch abreviation of adaptive temperature limit indicator) was developed in The Netherlands (ISSO, 2004). The ATG-method distinguishes three levels of thermal comfort (see figure 1). Level A corresponds to 90% thermal acceptability and is applied in buildings with high performance requirements to thermal comfort. Level B corresponds to 80% thermal acceptability, means good indoor thermal comfort and is the standard level. Level C, finally, corresponds to 65% thermal acceptability and is only applied in temporary situations in existing buildings. The minimum and maximum limiting indoor temperatures on a given day depend on the effective outdoor temperature

$T_{e,ref}$, i.e. the running mean external temperature of the given day and three preceding days with weighting factors in sequence of 1, 0.8, 0.4 and 0.2.

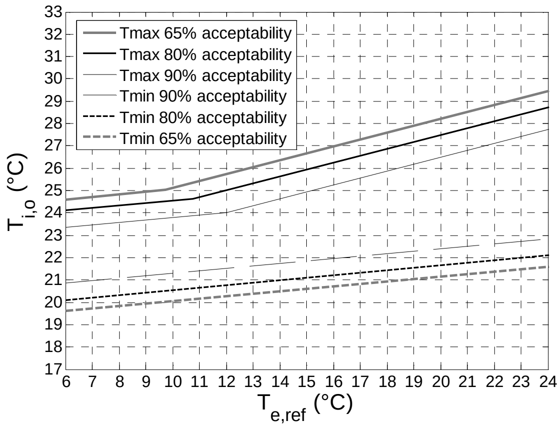

Figure 1: ATG-method in naturally ventilated buildings: limiting internal temperatures

Simulation model

Internal temperatures in a naturally ventilated building 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. Therefore, 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). The existing coupling between TRNSYS (Klein et al., 2000), a transient multizone thermal simulation model, and COMIS (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. In TRNSYS, a zone is represented by two temperatures: the homogeneous air temperature and the so-called star temperature (Seem, 1987). The star temperature is a weighted average of the zone air temperature and the surface temperatures of the walls surrounding the zone. The air temperature is solved from the convective heat flow balance of the zone, the star temperature is solved from the combined convective and radiation heat flow balance. The star temperature concept is introduced to facilitate the calculation of conduction heat loss over a wall, modeled by transfer functions (Klein et al., 2000). These relationships describe the heat flux at one side of the wall varying in time, depending on a change of the heat flux at the other side of the wall or on a change of the surface temperature at one of both sides of the wall.

In COMIS, each zone is represented by single values for air temperature and pressure. Air flow paths connect the zones to each other and to the outdoors. The flow rates are related to the pressure difference over the flow path by non linear equations. The air flow through vertical large openings like windows and doors is calculated as a two-directional gravitational air flow by the orifice equation. Closed large openings, fans out of action and air leaks are represented by the power law equation. Wind pressure coefficients, relating the wind pressure at a building to the wind velocity, are attributed to external nodes. 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 (Haas et al., 2002).

Uncertainty analysis

To analyse the uncertainty on the thermal comfort, given the uncertainty on the input parameters, 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).

Sensitivity analysis (Saltelli et al., 2000)

Sensitivity analysis studies, qualitatively or quantitatively how the variation in the output of a model is attributed to different sources of variation, i.e. boundary conditions, building properties and model assumptions. Global sensivity, based on a Monte Carlo analysis (MCA), is applied in this paper. Global sensitivity incorporates the influence of the whole range of variation and distribution of the input parameter and evaluates the effect of one parameter while all other parameters are varied as well.

The standardized regression coefficient (SRC) ranks and quantifies the effect of the input parameters on the thermal comfort in a naturally night ventilated office. Determination of SRC is based on linear regression analysis.

Following standardized linear regression model is made from a N*k sample with N elements of k input parameters (see above) (with j = 1,2,…, k; i = 1,2, …, N; x = input; y = output; b_j = regression coefficient):

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

The coefficients $\frac{b_j \hat{s}_j}{\hat{s}}$ are called standardized regression coefficients or SRCs. When the input parameters x_j are independent, the SRCs provide a measure of variable importance since SRC measures the effect of the variation of an input parameter x_j with a fixed fraction of its standard deviation on the variation of the output y, while all other input parameters equalize their expected value. Both the distribution of the input x_j and its impact on the output affect the SRC.

Using SRC, the model coefficient of determination (R_y^2) has also to be calculated to evaluate how well the linear regression model reproduces the actual output. R_y^2 represents the fraction of variance on the output that can be explained by the regression model. For a good estimation, the model coefficient of determination has to be close to unity.

SIMULATION

Natural night ventilation by single-sided and cross ventilation in a single office, based on an office on the first floor in the PROBE building (Limelette, Belgium) (Heijmans and Wouters, 2002), are studied. Figure 2 shows the model for single-sided natural night ventilation, i.e. the real situation: an office on the west side with vertical louvres and a part of the corridor. In addition, figure 3 shows the cross ventilation case: two identical offices on the east and the west side of a central corridor. Horizontal louvres with an affective area of 2% of the floor area according to design rules in (van Paassen et al., 1998) are provided above the windows and internal doors. The louvres in the façade are automatically opened and closed by bottom hung windows.

Boundary conditions, building characteristics and modelling assumptions of both natural night ventilation cases are given in the following paragraphs. All the input parameters of the thermal and ventilation simulation model 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. This means a parameter is included in this interval with a probability of 0.98.

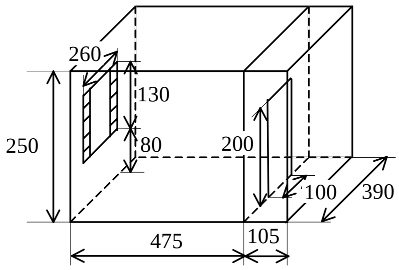

Figure 2 Two-zone model of single-sided natural night ventilation

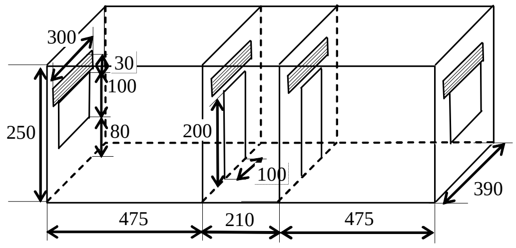

Figure 3 Three-zone model of cross natural night ventilation

Thermal model

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 30. The internal heat gains are shown in table 1. The heat gains of computers, monitors, printers and lighting are multiplied by a diversity factor. This factor takes into account that not all equipment is in use all the time or is emitting its actual peak heat gain (Wilkins and Hosni, 2000). The total internal heat gains vary from 15.4 to 24.4 W/m² in the offices and equalize 6 W/m² in the corridor.

Table 1
Internal heat gains

		LOW	**MEDIUM**	**HIGH**
People	W/pers.	75	80	85
	Diversity	1.00	1.00	1.00
PC + screen	W/pc.	110	135	155
	Diversity	0.67	0.80	1.00
Lighting	W/m²	10	10	10
	Diversity	0.67	0.80	1.00
Laser printer	W/pc.	130	130	130
	Diversity	0.10	0.15	0.20
Total (W/m²)		27.0	28.6	30.0
Total with diversity (W/m²)		**15.4**	**19.2**	**24.4**

Average dimensions (in cm) are given in figure 2 and 3. The standard deviation is assumed to be ± 2 cm (De Wit, 2001). Wall compositions are shown in table 2. External and internal sunblinds are provided on respectively the west and east window and are automatically controled to be lowered from an irradiation of [225;275]. The solar transmission coefficient of the glass with external sunblinds varies from 0.1 to 0.2. The solar absorption of the internal curtains is 0.1, the reflection coefficient towards the window has a value between 0.5 and 0.7 (CEN, 1998).

Table 2
Wall composition

WALL	COMPOSITION
Floor	Reinforced concrete
External wall	Brick cavity wall
Roof	Reinforced concrete + 11.5 cm insulation
Internal wall offices	Gypsum board + 5cm insulation
Internal wall corridor	Brick wall
Window	Double glass with low-e coating, cavity filled with argon + Aluminium frame + shading

Table 3
Material properties: mean (μ) and standard deviation (σ) of conduction (λ), density (ρ), solar absorption (a) and specific heat (c)

MATERIAL		λ (W/mK)	ρ (kg/m³)	a (-)	c (J/kgK)
Façade brick	μ	0.90	2000	0.49	840
	σ	0.06	6	0.06	13
Internal brick	μ	0.54	1500	0.49	840
	σ	0.04	6	0.06	17
Reinforced concrete	μ	1.70	2400	0.72	840
	σ	0.16	20	0.04	35
Light concrete	μ	0.25	850	0.68	840
	σ	0.02	17	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	15	0.05	86
Air cavity: R (mK/W)	μ	0.16	-	-	-
	σ	0.02	-	-	-

Table 3 shows the material properties: mean values of the conduction coefficient, density and specific heat are taken from the Belgian standard (BIN, 2001). Uncertainties on these values are caused by temperature and humidity variations and are calculated according to (ISO, 1999; IEA, 1991), taking into account a temperature difference of 10°C and a humidity ratio depening on the kind of material (CEN, 2000). Glass properties are not varied: the window has a solar transmission coefficient g of 0.6 and a transmittance coefficient U of 1.1 W/m²K. Although, the convective heat transfer coefficient is varied as explained further. Solar absorption coefficients are taken from (Clarke et al., 1990).

The convective heat transfer coefficient on external surfaces depends on the local wind velocity on site (ASHRAE, 2001). The internal convective heat transfer coefficient by natural convection is function of the temperature difference between the concerned surface and the air Δθ and can be summarised as follows:

$$\alpha_{ci} = C(\Delta\theta)^n \quad (4)$$

In equation 4, C and n are semi-empirical coefficients which were determined amongst others by (Awbi and Hatton, 1999; ASHRAE, 2001; Alamdari and Hammond,1983; Khalifa and Marshall,1990) and given in table 4.

A time step of 15 min is chosen. Internal seperations between the concerned office and other offices are assumed to be adiabatic. The offices are assumed to be occupied during working hours from 8h to 17h.

Table 4
Semi-empirical coefficients C and n defining internal convective heat transfer coefficient

α_{ci}	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]

Ventilation model

The wind velocity on site at building height is calculated from the meteorological wind velocity $\bar{v}_{ref}$ in equation 5. The boundary heights z_{bound} and the roughness parameters respectively on site and at the meteorological station a_0 and a_m are given in table 5 (Feustel et al., 2001).

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

Table 5
Roughness parameter a and boundary height z_{bound} at meteo station and on site

LOCATION	TERRAIN DESCRIPTION	z_{bound} (m)	a (-)
Meteo station	Cultivated open fields	60	[0.149;0.171]
On site	Countryside and spread habitat	60	[0.182;0.257]

Table 6 shows the average wind surface pressure coefficients Cp for various wind directions (0° is north). The uncertainty interval for the Cp coefficient on the façade and flat roof equalize respectively the mean value ± 0.15 and ± 0.2 and are correlated.

The air tightness is characterised by a n_{50}-value from 2 to 8 vol/h (BBRI, 1999) and modeled by cracks in the offices at floor and ceiling height. During working hours, 22.5 to 27.5 m³/h.pers of ventilation air is supplied in the offices and a quarter thereof is mechanically extracted in the corridor. The flow is preheated and the heating also starts working when the internal air temperature is lower than heating setpoint, which is equal to the setpoint for night ventilation – 1°C. The opening of the windows on the inside of the façade louvres are automatically controled as shown in table 7 (Martin and Fletcher, 1996). Night ventilation in the west and east office is separately controlled. In addition, table 8 describes the characteristics of the natural night ventilation openings (Flourentzou et al., 1998; Liddament, 1996). The internal doors are assumed to be closed.

Table 6
Wind pressure coefficient Cp

C_P	WIND DIRECTION (°)							
	0	**45**	**90**	**135**	**180**	**225**	**270**	**315**
East façade	-0.35	0.06	0.25	0.06	-0.35	-0.6	-0.5	-0.6
West façade	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	0.25	0.06
Flat roof	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6

Table 7
Control system natural night ventilation

NATURAL NIGHT VENTILATION IS IN OPERATION IF THE CONDITIONS BELOW ARE FULFILLED
Previous day
$\theta_{i,max}$ > [21; 25]°C $\theta_{e,max}$ > [18; 20]°C
At that moment
[21; 23]h < time < [5;7]h θ_{si} > [21; 23]°C θ_i - θ_e > [1; 3]°C θ_e > [11; 13]°C

Table 8
Natural ventilation opening characteristics

OPENING	A_{EFF} (m²)	C_D (-)	C (kg/s.m.Pa)	n (-)
Vertical louvre	0.44	[0.4;0.8]	0	0.6
Horizontal louvre + bottom hung window	0.38	[0.4;0.8]	0	0.6
Internal door	2.0	[0.4;0.8]	[0.0008; 0.0024]	0.6

Comparison to measurements

Before discussing the uncertainty and sensitivity of the thermal comfort in a natural night ventilated office, the simulated operative internal temperature and ventilation rate in a west office on the first floor in the Probe buiding are first compared to measurements (Heijmans and Wouters, 2002).

Measurements of internal temperatures and weather data on site were carried out from June to August 2001. Unfortunately, the ventilation rates, the internal heat gains and the use of the louvres were not measured. For the former, the simulation results are compared to ventilation rates, measured in the summer of 1998. In addition, the internal heat gains from the same summer period of 1999 were taken. The latter was derived from temperature measurements in the concerned office. Contrary to the model for the uncertainty and sensitivity analysis, described in the former paragraphs, the opening of the night ventilation louvres was controlled by the user. Moreover, the office building was shielded by other buildings from a wind direction of 180° (south) to 315° (northwest). Consequenly, the wind pressure coefficient Cp was reduced for these wind directions. All these assumptions were taken into account.

Figure 4 shows the distribution of the night ventilation flow rates averaged out over the night. The average flow amounted to 3.2 vol/h and varied from 1.9 to 4.4 vol/h. These results agree rather good with the measurements from the summer of 1998. An average night ventilation flow of 3.7 vol/h was noticed in a single office on the west side (Heijmans and Wouters, 2002). In addition, the simulated and measured operative internal temperatures are compared in figure 5. Taking into account that the internal heat gains are taken from another year, the simulated and measured temperatures agree rather well. Although, a difference in heat storage is noticed. The simulated internal temperature decreases and increases faster during respectively the night and day than the measured temperature.

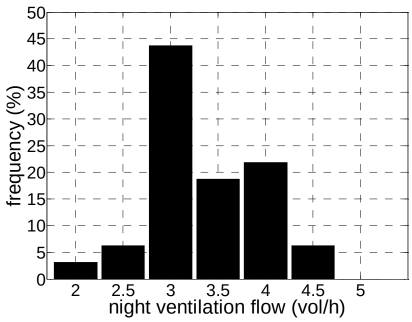

Figure 4 Distribution of average single-sided night ventilation rate in a west office of Probe-building

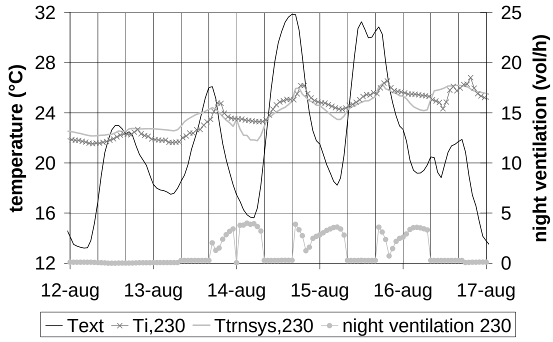

Figure 5 Comparison of simulated and measured operative internal temperature in a west office of Probe-building.

DISCUSSION

Uncertainty and sensitivity analysis, based on Monte Carlo Analysis, studies and compares the thermal summer comfort in a single-sided and cross night ventilated office. 500 independent Latin Hypercube samples are developed using Simlab software (POLIS, JRC-ISIS, 2003). This number exceeds largely the minimum of 1.5 x 72 factors = 108.

Uncertainty analysis

Figure 6 shows the result of the uncertainty analysis for a single-sided and cross night ventilated office on the west side. In this paper, only the temperature exceeding hours are taken into account to determine the comfort level in the ATG-method. A good thermal comfort, i.e. level A or B, is found in a single-sided ventilated office with a probability of only 0.15. There is even a probability of 0.42 that the office belongs to neither of the three levels. The same trend is noticed in a cross ventilated office. Although, due to a higher ventilation rate, good thermal comfort has a larger probability in the latter case, i.e. 0.34. High probability of thermal comfort labelled as 'level C' or 'no level' is caused by high temperatures inside occurring on some cool summer days after a warm day ($14 < T_{e,ref} < 16°C$). These exceeding hours are critical defining the comfort level.

In addition, the probability of good thermal comfort in a cross ventilated office on the west and the east side are compared in figure 7. Thermal comfort has a much smaller probability in the office on the east than on the west side because of higher solar heat gains - internal sunblinds are applied - and a lower cooling capacity of the night cooling. Because westerly wind frequentlier occurs in Belgium than easterly, the outside air cooling down the building structure, is mostly warmer in the east than in the west office. Moreover, when the west office has been cooled down, the bottum hung windows in this office consequently close and the night cooling in the east office has to continue in the less capacitive single-side mode.

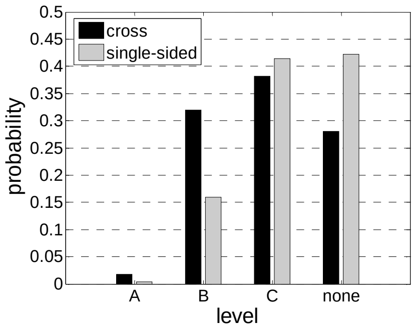

Figure 6 Distribution of thermal comfort of single-sided and cross night ventilation in a west office.

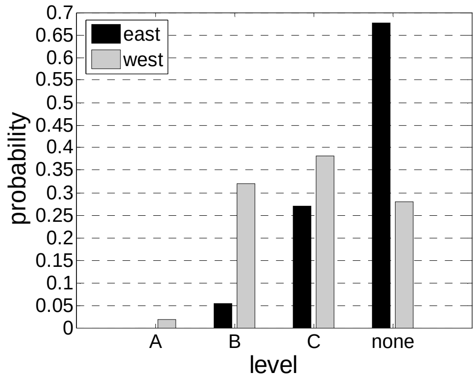

Figure 7 Probability of the thermal comfort (ATG) of cross night ventilation in a west and east office.

Sensitivity analysis

Sensitivity analysis defines the impact of all input parameters on thermal comfort, characterized by ATG. As the levels of the ATG method are not suitable for this purpose, the degree hours exceeding the line of neutral comfort (see equation 6) (de Dear and Brager, 2002) are determined.

if $T_{e,ref} > 17.4$ then $T_{i,n} = 17.8+0.31*T_{e,ref}$ (6)

else $T_{i,n} = 21.45+0.1*T_{e,ref}$

The standardized regression coefficients (SRC) of all input parameters are calculated. The regression model approaches the real output very well as the model coefficient of determination equals 0.98. The most influential parameters in case of single-sided night ventilation are summarized in table 9. The sign of the impact of the parameters differ: a positive sign means that increasing the concerned parameter decreases the thermal comfort and vice versa.

Table 9
Most influential parameters on thermal comfort with single-sided night ventilation

PARAMETER	SRC
Internal heat gains	0.84
$C_{d,opening}$	-0.21
External solar absorption	0.20
Air tightness	-0.18
Controlling night ventilation ($T_{e,min}$ by day)	0.18
Thermal conduction internal wall	-0.16
Controlling night ventilation ($T_{i,min}$ by day)	0.12
Controlling night ventilation ($T_{e,min}$ by night)	0.11
Solar transmission of sunblinds	0.10
Start time night ventilation	0.09
Controlling night ventilation ($T_{i,min}$ by night)	0.08
Stop time night ventilation	-0.08
Roughness on site, defines external convective heat transfer	0.08
Controlling sunblinds	0.06

Following groups of factors can be distinguished:

- influencing heat gains: internal heat gains, properties of glass and sunblinds, external solar absorption façade (uninsulated wall)
- determining conduction and ventilation heat losses: thermal conduction façade, external convective heat transfer and air tightness
- defining night ventilation: control parameters, opening properties, internal convective heat transfer

The internal heat gains are noticed to largely have the greatest impact on thermal comfort.

The results of the sensitivity analysis in a single-sided and cross ventilated office on the west side are compared in figure 8. Roughly spoken, the same input parameters have an important effect on the thermal comfort except the wind pressure coefficient Cp and the temperature difference between inside and outside at night (DT_night), i.e. control parameter of night ventilation, which have a much larger effect in the cross ventilation strategy. Conversely, the size of the impact – and thus the order of importance – of some parameters differs a lot. On one hand, the air tightness, roughness on site – defining the local wind speed – internal convective heat transfer coefficient and some control parameters have a larger impact in a cross than a single-sided ventilated office. The SRCs of the internal heat gains, external solar absorption, night ventilation opening properties (discharge coefficient C_D) and the thermal conduction coefficient of the internal wall are on the other hand smaller in a cross than single-sided ventilated office.

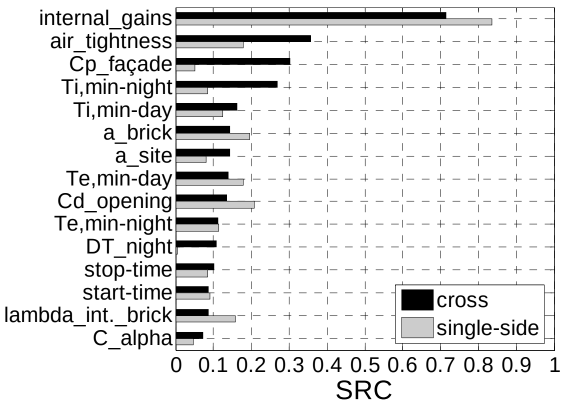

Figure 8 Most influential input parameters of cross and single-sided night ventilation compared

In addition, the results of the sensitivity analysis of an office equipped with a cross night ventilation on the east and the west side are compared in figure 9. The results are similar, except for the shading devices, which differ in both offices. Moreover, the impact of the discharge coefficient of the louvres is larger in the office on the east side. Conversely, the minimum internal temperature by day, i.e. a control parameter of the night ventilation, has a smaller impact in the office on the east side.

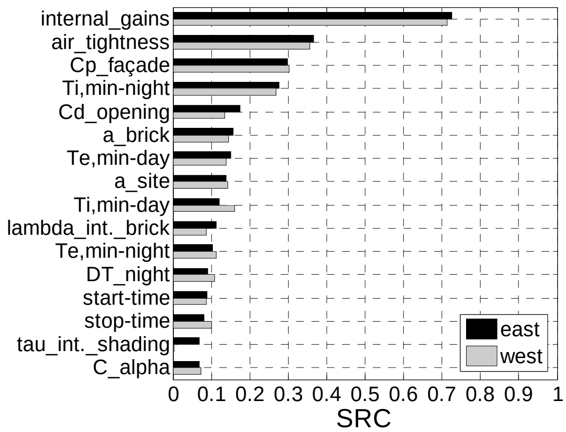

Figure 9 Most influential input parameters of cross night ventilation in a west and east office compared

CONCLUSION

Uncertainty analysis is used to investigate the uncertainty of the predicted thermal comfort in an office, cooled with natural night ventilation. A good thermal comfort has a larger probability in a cross than a single-sided ventilated office on the same wind direction. Although, the probability of a good thermal comfort, characterized by the adaptive criterion ATG, is only 0.15 to 0.34 in an office on the west side.

Moreover, sensitivity analysis defines the most important input parameters causing this uncertainty. Internal heat gains have the largest important impact on thermal comfort in both single-sided and cross night ventilated offices. Moreover, air tightness and the wind pressure coefficient largely affect the thermal comfort in case of cross ventilation. In addition, little difference in sensitivity is noticed between the thermal comfort in the office on the west and the east side when cross ventilation is applied.

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