Reliable Design of Natural Night Ventilation Using Building Simulation

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ABSTRACT

Natural night ventilation is an interesting passive cooling method in moderate climates. Driven by wind and stack generated pressures, it cools down the exposed building structure at night, in which the heat of the previous day is accumulated. Building simulation can predict the performances of this cooling technique. Nevertheless, the reliability of these results depends on the accuracy of the input data. Two practical guidelines are developed to ensure a reliable design using building simulation. First, the combination of a normal and extremely warm weather data is advised. Second, evaluating the uncertainty interval instead of one single value is recommended. These guidelines are derived from a general methodology to evaluate the design of natural night ventilation using building simulation to consider the uncertainties in the input. The importance of these guidelines is shown in the evaluation of the reliability of the design of natural night ventilation in the "Sint-Pietersnieuwstraat" office building (Belgium). An acceptable average thermal comfort level can be noticed in normal weather conditions. However, a large variation in thermal comfort is observed and the criteria for good thermal comfort are not met in extremely warm weather. The design of natural night ventilation cannot ensure reliable thermal comfort in this office building.

INTRODUCTION

Natural night ventilation uses the outside air at night as a heat sink to cool down a building. Cold outside air enters the building at night and cools down the exposed building structure, in which the heat of the previous day is accumulated. The heated air subsequently leaves the building. This airflow is driven by natural ventilation forces as thermal buoyancy (stack effect) and wind. Consequently, the indoor temperature peaks during daytime are reduced and postponed. The cooling mechanism of natural night ventilation is based on the convective heat transfer from the exposed building structure to the cold air flow at night, i.e. when the indoor-outdoor air temperature difference is maximal. By day, these walls are (re)heated by solar and infrared radiation and room air convection. This has three important consequences. First, to make natural night ventilation work, heat storage in the internal structure is necessary (Givoni, 1994 & Balaras, 1996). The phase difference between heat transfer to and from the building structure has to be bridged. Second, hot and moderate climates with a large diurnal temperature difference over the summer are best suited (Kolokotroni, 1995). Third, since this technology provides primarily sensible cooling, natural night ventilation is highly discouraged in humid climates. The humidity ratio of the outside air should be less than 15 g/kg dry air (Kolokotroni, 1995).

Natural night ventilation is applied to cool several office buildings in Belgium, e.g. Renson in Waregem (Breesch et al., 2004), SD Worx in Kortrijk (Breesch et al., 2005) and PROBE in Limelette (Heijmans and Wouters, 2002). Thermal comfort was examined by monitoring the indoor temperature and the relative humidity. These examples show that the requirements of good thermal comfort can be fulfilled in a moderate climate in case of a low cooling load. However, natural night ventilation does not perform well when the outdoor temperatures are extremely high (Breesch, 2006).

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Building simulation can predict the performances of natural night ventilation. Nevertheless, the reliability of these simulation results depends on the accuracy of the input data. The uncertainty of these data can be very important in the decision process. Therefore, it seems essential that the various decision makers are informed about the potential uncertainties (Wouters, 2000). Designers require information on performance robustness rather than performance quantification with no account taken of uncertainty to make effective use of simulation (Macdonald, 2002). Uncertainty and sensitivity analysis are interesting methods to deal with the uncertainties in the input. A probability distribution curve, i.e. the result of an uncertainty analysis, gives substantially more information than the outcome of a single simulation (Wouters, 2000). The result of a sensitivity analysis, i.e. a list of influencing input parameters, helps the designer to increase the reliability of the design of natural night ventilation.

Both analyses have already been applied in building simulation. De Wit (2001) concluded that the variability in the thermal comfort performance is significant in a naturally ventilated office building. Macdonald (2002) implemented uncertainty analysis in the code of the building simulation software ESP-r (ESRU, 2005). Pietrzyk and Hagentoft (2005) developed a probabilistic model to predict the distribution of the air change rate for a naturally ventilated house based on variations in climatic conditions. Sensitivity analysis is widely used in model validation, see a.o. Borchiellini and Fürbringer (1999), Aude et al. (2000).

In this paper, practical guidelines to ensure a reliable design of natural night ventilation using building simulation are discussed. First, the methodology to predict the performances of natural night ventilation using building simulation taking into account the uncertainties in the input is discussed. Then, the practical guidelines derived from this general methodology are described. Finally, a case study, which shows the importance of these guidelines evaluating a design with building simulation, is presented.

METHODOLOGY

Breesch (2006) described the methodology to predict the performances of natural night ventilation using building simulation and taking into account the uncertainties in the input. The variation on the reached thermal comfort as well as the input parameters causing this uncertainty are determined. This general methodology includes the following parts. First, to evaluate the performances of natural night ventilation, a suitable criterion of thermal comfort is selected. Second, to predict these evaluation criteria, an appropriate building simulation tool is chosen. Then, a generic building model is created and the uncertainties on the input parameters are estimated. Finally, uncertainty and sensitivity analysis are used to take the uncertainties in the input of this tool into account.

Thermal Comfort

Thermal comfort is chosen to evaluate the performances of natural night ventilation, i.e. the achieved indoor climate. Fanger (1972) showed that how people react to the thermal indoor environment depends on both indoor environmental (air and radiant temperature, air velocity and relative humidity) and personal properties (metabolism, activity level and clothing). The air and radiant indoor temperatures are calculated. The other parameters are assumed as follows: a metabolism of 70 W/m body's area, a clothing resistance of 0.7 Clo (light working clothes and a chair) and an air velocity of 0.1 m/s. The internal vapor pressure is calculated from the weekly-mean values of the external vapor pressure and temperature as proposed by Hens (1992). To consider the differences in individual perception, Fanger measured the comfort sensation of different test persons. The prediction of the average sensation of a given environment or PMV (predicted mean vote) and the deviation of this average value or PPD (predicted percentage of dissatisfied) are derived from these tests.

A suitable long-term evaluation criterion is the weighted temperature excess method (GTO) (van der Linden et al., 2002). This criterion is based on this PMV model and determined as follows. 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. The weighted temperature excess hours are the sum of these hourly weight factors during working hours.

A number of weighted working hours less than 150h, means a good thermal summer comfort. This corresponds to 5% excess hours, i.e. 100h, with on average 15% of dissatisfied people (or WF = 1.5). A comparable long-term evaluation criterion is included in the standard EN ISO 7730-1996 (ISO, 1996).

Building Simulation Tool

To evaluate the performances of a designed natural night ventilation system in a particular project in detail, building simulation is used. A coupled thermal and ventilation model, which iterates the mass and energy balance per zone till convergence, is necessary to simulate natural night ventilation. The internal temperatures in a naturally ventilated building depend on the ventilation flow rates. And as natural night ventilation is partly temperature driven, these flow rates in turn are a function of the indoor air temperatures (Breesch and Janssens, 2002).

The existing coupling between TRNSYS (Klein et al., 2004), a transient multi-zone thermal simulation model, and COMIS (Feustel, 1999 & Dorer et al., 2001), a multi-zone infiltration and ventilation simulation model, is chosen to predict the thermal comfort in a building, cooled with natural night ventilation. Both simulation programs subdivide the building into 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. This is modelled according to transfer function relationships (Klein et al., 2004).

In COMIS, each zone is represented by single values for the air temperature and pressure and connected to other zones and the external environment by air flow paths. A non linear equation relates the flow rate through a flow path to the pressure difference. Air leaks, air leakages in closed large openings and fans out of action are represented by the power law equation. The airflow through large vertical openings like windows and doors is two-directional steady-state gravitational. The mass flow for each part of the opening with different flow direction, caused by density differences, is calculated by the orifice equation. (Feustel, 1999). The steady-state mass conservation laws for each zone constitute a set of non-linear equations. An iterative solution defines the pressure in each zone and the air flow through every link.

The thermal building model TRNSYS and the air flow model COMIS have been validated (Lomas et al., 1997 & Fürbringer et al., 1996). Delsante and Aggerholm (2002) studied control strategies for hybrid ventilation systems and compared the results of TRNSYS-COMIS to those of three other tools. The differences between maximum and mean temperatures in summer between the tools are small but consistent. The tools agree well on the effect of mechanical night cooling. Therefore, TRNSYS-COMIS seems a suitable tool to predict the performances of natural night ventilation.

Uncertainty and Sensitivity Analysis

To take the uncertainties on the input in the building simulation tool into account, uncertainty and sensitivity analysis are applied. The variation on the reached thermal comfort as well as the input parameters causing this uncertainty are determined.

Monte Carlo Analysis (MCA) is chosen because it requires a restricted number of simulations. In addition, both sensitivity and uncertainty analysis can be performed using this same method. MCA has already been successfully implemented in building simulation (de Wit, 2001 & Macdonald, 2002). MCA performs multiple evaluations with randomly selected model input factors and can deal with correlated input parameters. The following steps are successively carried out: (1) selection of a range and distribution for each input parameter, (2) sample generation from these distributions, (3) evaluation of the model for each element of this sample, (4) uncertainty analysis and (5) sensitivity analysis.

Various sampling procedures are used in MCA studies. The Latin Hypercube sampling (LHS) strategy is used because this method ensures full coverage of the range of each variable. The determination of the uncertainty analysis is straightforward. The expected average value and variance of the output y are estimated. The global sensitivity indicator Standardized Regression Coefficient (SRC) is selected. SRC is based on regression analysis. This coefficient measures the effect of the variation of an input parameter with a fixed fraction of its standard deviation on the variation of the output, while all other input parameters equalize their expected value. This means that both the distribution of the input and its impact on the output affect the SRC. Using SRC, the model coefficient of determination 5\ has also to be calculated to evaluate how well the linear regression model reproduces the actual output. For a good estimation, this coefficient has to be close to unity (Saltelli et al., 2000).

Generic Building Model

A building model has to be made to predict the generic performances of natural night ventilation by the building simulation tool TRNSYS-COMIS considering the uncertainties in the input. A typical office building is taken into consideration: a two-story building with identical small offices on both sides of a central corridor. The corridors on the various floors and the stairwells are assumed to be disconnected. Consequently, the building is simplified by taking only the cross-section of one floor into account. This generic building model includes 3 zones: two identical offices separated by a central corridor is shown in Figure 1 for cross night ventilation. The offices are situated on an intermediate floor, in this case the lowest floor of a two-story office building. Internal separations between the concerned office and adjacent offices are assumed adiabatic. A similar model is also used by van Paassen et al. (1998) in their pre-design tools for natural night ventilation.

Uncertainties on Input Parameters

All input parameters of this building model are assumed to be normally distributed. Breesch (2006) estimated these distributions from data in the literature and standards. The given ranges correspond to $\mu - 2\sigma;\mu + 2\sigma$, where μ and σ are

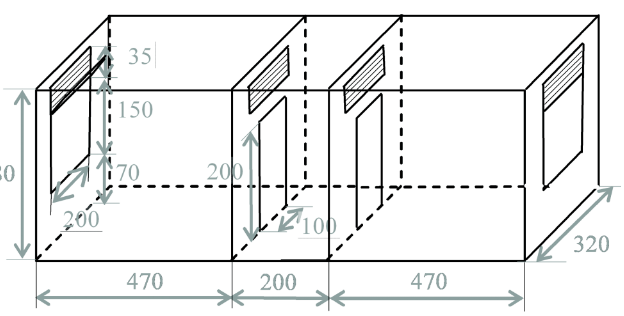

Figure 1 *Generic building model provided with cross night ventilation openings.*

respectively the average and standard deviation. This means a parameter is included in this interval with a probability of 0.98.

Figure 1 shows the average dimensions of the concerned offices (in cm): an internal floor area of 15m^2 is assumed. The geometrical properties of each component are measured from the internal surfaces (CEN, 2004a). The total building height averages 7.3m. Due to irregularities in the construction process, the realized geometry may slightly deviate from the geometry given in the design specifications with [-0.02, 0.02] m (de Wit, 2001). The composition of the walls is shown in Table 1. The basic office includes an exposed ceiling, a raised floor, a heavy façade and light internal walls.

Table 2 shows the thermophysical properties of the layers, which define the heat transfer and storage. The mean thermophysical properties (μ) are assumed for dry materials listed in the Belgian standard NBN B62-002/A1 (BIN, 2001). The uncertainties of the thermal conductivity, density and specific heat capacity are caused by variations in temperature and moisture content and heterogeneity of products. A moisture content for each material, determined by EN 12524 (CEN, 2000) and a temperature variation of 10°C are assumed. The variation in thickness is caused by lack of information on the exact properties (de Wit, 2001) and derived from the sensitivity analysis of building thermal modeling of Pinney et al. (1991). Furthermore, Macdonald (2002) derived for every material an average value and a standard deviation of the solar absorption coefficient from Clarke et al. (1990).

The average glazing area of the window measures 25% of the internal façade area. The thermophysical properties of glazing are not varied: a fixed thermal resistance is assumed 0.74 m^{2}K/W. The solar heat gain coefficient of the window has a g-value of 0.60. An uncertainty of $\pm$ 0.02 is estimated from product information (Glaverbel, 2005). Exterior moveable sunblinds are provided on all orientations. The solar heat gain coefficient for the combined system of glass and sunblinds varies from 0.10 to 0.20 (Hens, 1999). These sunblinds are automatically controlled. They are lowered from an incident solar radiation on the particular façade of 150 W/m^2 (ISSO, 1994). The uncertainty is estimated to be 10% of this value.

The convective heat transfer coefficient on external surfaces depends on the local wind velocity on-site (ASHRAE, 2005). The internal convective heat transfer coefficient by natural convection is a function of the temperature difference between the concerned surface and the air ($\Delta\theta$):

$$\alpha_{ci} = C(\Delta\theta)^n \tag{1}$$

where C and n are semi-empirical coefficients, which were determined amongst others by Awbi and Hatton (1999), ASHRAE (2005), Alamdari and Hammond (1983), Khalifa and Marshall (1990), Khalifa (2001). The uncertainty of C and n is derived from the difference between the maximum and minimum value in these models. These coefficients are shown in Table 3 for a vertical, a horizontal surface with a buoyant (i.e. an upward) and a stably stratified flow.

The airtightness is characterized by an average n_{50}-value of 3.9 h^{-1} and a standard deviation of 3.8 h^{-1}. These values are derived from measurements by Litvak et al. (2000). This value corresponds to the measured global airtightness in nine new Belgian apartments (BBRI, 1999). The average n_{50} in these flats is 4.1 h^{-1}; a wide variation is noticed from less than 2 h^{-1} to more than 8 h^{-1}. This airtightness is modelled by four cracks in each office façade: at floor and ceiling height and at the bottom and the top of the window.

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 constantly emitting its actual peak heat gain (Wilkins and Hosni, 2000). This uncertain nature of building use causes the uncertainty of the internal heat gains. Three scenarios of internal heat gains are made depending on the use and heat production, based on the scenarios proposed by Wilkins and Hosni (2000). The diversity is assumed equal in the case of people, equipment and lighting. Table 4 shows that the total heat gains (including diversity) vary from 17.8 to 28.1 W/m^2 for a single office of 15 m^2 occupied by one person. The convective-radiant ratio is not varied: 70%- 30%. No variation is assumed of the internal heat gains in the corridor. ISSO (1994) suggests 6 W/m^2. These values are assumed constant during working hours, i.e. from 9h to 18h daylight savings time.

External louvres are provided in the façade to ensure natural night ventilation flow rates. Horizontal louvres are also situated above the windows and internal doors as shown in Figure 1. An effective opening area of Figure 2 to 3% of the

Table 1. Wall Composition

Raised Floor		Heavy Façade		Light Internal Wall	
Layer	**d (cm)**	**Layer**	**d (cm)**	**Layer**	**d (cm)**
Hollow core concrete slabs	13	Façade brick	9	Gypsum board	1
Reinforced concrete	3	Air cavity	2	Insulation	5
Light concrete	5	Insulation	8	Gypsum board	1
Air cavity	50	Internal brick	14		
Plywood	1.8				
Carpet	0.5				

Table 2. Uncertainties on the Thermophysical Properties

Material		λ, W/m·K	ρ, kg/m^3	a	c, J/kg·K	d, m
Façade brick	μ	0.90	2000	0.49	1000	0.090
	σ	0.06	20	0.06	13	0.001
Internal brick	μ	0.54	1500	0.49	1000	0.140
	σ	0.04	15	0.06	17	0.001
Reinforced concrete	μ	1.70	2400	0.72	1000	0.030
	σ	0.11	24	0.04	38	0.002
Light concrete (screed)	μ	0.24	850	0.72	1000	0.030
	σ	0.02	9	0.04	84	0.004
Hollow core concrete slab	μ	1.09	1800	0.72	1000	0.130
	σ	0.10	18	0.04	47	0.010
Insulation (mineral wool)	μ	0.040	50	—	1000	0.080
	σ	0.001	0.5	—	10	0.004
Gypsum board	μ	0.25	900	0.40	1050	0.0100
	σ	0.03	9	0.05	86	0.0005
Carpet	μ	0.06	200	0.60	1300	0.004
	σ	0.008	2	0.03	51	0.001
Plywood	μ	0.24	850		1880	0.018
	σ	0.03	9		335	0.001
Air cavity: R, m^2·K/W	μ	0.16	—	—	—	—
	σ	0.01	—	—	—	—
Aluminum window frame: U, W/m^2·K	μ	3.8	—	0.53	—	—
	σ	0.2	—	0.06	—	—

Table 3. Semi-Empirical Coefficients *C* and *n* of 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)

floor area is provided, according to the design rules of van Paassen et al. (1998). The average value of the discharge coefficient C_d is assumed 0.6 for a sharp-edged opening. An uncertainty of ± 0.1 is assumed (Flourentzou et al., 1998). These external louvres are automatically opened and closed by bottom-hung windows. Table 5 proposes an automatic control system, based on the research of Martin and Fletcher (1996). A minimum zone setpoint is specified to prevent overcooling. This value is related to the heating setpoint to avoid the situation where overcooling is followed by heating. Night ventilation is only permitted when the zone temperature exceeds

Table 4. Internal Heat Gains in a Single Office (15 m^2) with One Person

Internal Heat Gains		Low	Medium	High
People	W/pers.	75	80	85
	Diversity	0.67	0.75	1.00
PC + screen	W/pc.	110	135	135
	Diversity	0.67	0.75	1.00
Lighting	W/m^2	10	10	10
	Diversity	0.67	0.75	1.00
Laser printer	W/pc.	130	130	130
	Diversity	0.33	0.4	0.4
Total (including diversity), W/m^2	**1 pers.**	**17.8**	**21.7**	**28.1**

the external temperature. Furthermore, night ventilation on weekends is recommended, particularly for peak ambient conditions. The following parameters are added in a realistic control system to prevent condensation (Breesch et al., 2002, 2005): no rainfall and an indoor relative humidity smaller than 70% at night. The uncertainty of the temperatures in this control system are assumed to be the average accuracy of the temperature loggers, used in the monitoring of the building management system (Onset, 2005).

A mechanical ventilation system by day is provided. The design value of the ventilation system is 36 m^3/h and corresponds to a medium to moderate indoor air quality defined in the European ventilation standard for non-residential buildings EN 13779 (CEN, 2004b). The variation on these airflows is assumed 10%. The flow rates are directly supplied to the office and extracted from the corridor. A heating system is implemented to ensure good thermal comfort during office hours at the beginning and the end of the simulation period, where low morning temperatures occur. This heating set point equals the set point of night ventilation minus 2°C. No mechanical cooling is provided.

Thermal comfort in a building, cooled with natural night ventilation, depends on the external weather conditions. Hence, outdoor temperature, irradiation, wind velocity and direction, are important boundary conditions in this evaluation process. Therefore, which data set is to be used has to be well thought out. Crawley (1998) recommends the use of a typical as well as a hot/sunny weather data set to evaluate the performances of passive cooling in building simulation. Measurements in the meteorological station of Uccle support this recommendation for the outdoor temperature. The climatological daily average value from June to August of 16.5°C is exceeded every year during the last 10 years (see Figure 2). In addition, the Intergovernmental Panel on Climate Change (IPCC, 2002) noticed an increase of the global surface temperatures of 0.6 ±0.2°C since the late 19th century. Most of this increase has occurred in two distinct periods, 1910 to 1945 and since 1976. The rate of temperature increase since 1976 has been over 0.15°C/decade. In addition, an increased air temperature is noticed in the urban environment compared to the rural where meteorological stations are located. This phenomenon has a large impact on the performances of natural night ventilation: the efficiency of this technique is significantly reduced in this urban environment (Geros et al., 2005).

Two weather data sets for Uccle (Belgium) are selected, including normal and extremely warm temperatures. Meteonorm (Meteotest, 2003) creates synthetic hourly weather data, based on the climatological normals of 1961-1990 of the meteorological station Uccle (Belgium). These normalized values of the World Meteorological Organization include measured monthly values for air and dew point temperature, global solar radiation on a horizontal surface, sunshine duration, precipitation, and days with precipitation, wind speed and direction. The extremely warm temperatures have an occurrence once every 10 year. Figure 3 compares the extreme weather data set for Uccle (Belgium) to the typical weather data set and measurements of the meteorological station of 2002 and 1995. Figure 3 shows that the summer of 2002 was relatively warm with daily average temperatures higher than normal. The summer of 1995 was extraordinarily warm and is used as an extreme weather data set in the Dutch regulations (van der Linden et al., 2006). The absolute values of temperature in the extreme weather data set are significantly higher compared to the values in a typical Meteonorm data set. However, the daily temperature range is comparable in both data sets. The average temperature and the temperature distribution of the extreme weather data of Meteonorm are comparable to the measurements of 2002 rather than to those of 1995.

Wind is a highly variable and irregular physical phenomenon and causes uncertainty in the prediction of the airflows of natural ventilation. In a multi-zone ventilation model, the wind pressures on buildings are calculated from the wind characteristics of meteorological measurements. The average meteorological wind velocity at reference height of 10 m $\bar{v}_{ref}$

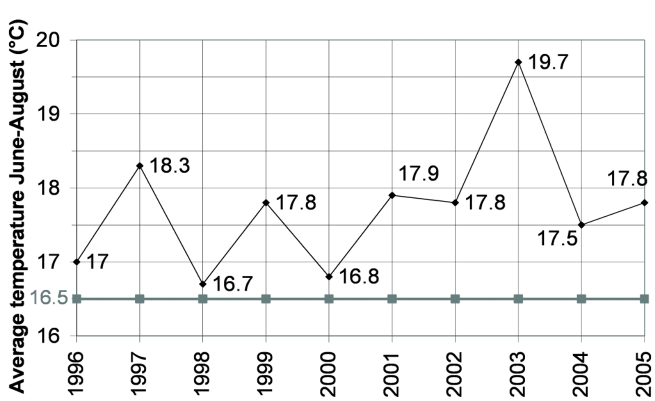

Figure 2 *The average summer temperature measured in the meteorological station Uccle (Belgium) (based on data of RMI).*

Table 5. Controlling Natural Night Ventilation

Natural night ventilation is in operation if the conditions below are fulfilled.
Previous day
$\theta_{i,max}$ > 23°C [22.5 – 23.0 – 23.5]°C
At that moment
22h < time < 6h
$\theta_{s,ceiling}$ > 22°C [21.5 – 22.0 – 22.5]°C
(= heating set point + 1°C)
$\theta_i - \theta_e$ > 2°C [1.5 – 2.0 – 2.5]°C
v < 7 m/s

θ_i : indoor temperature (°C)
θ_s : surface temperature (°C)
θ_e : exterior temperature (°C)
v: wind velocity (m/s)

Table 6. Roughness Class, Height z_0 and $\lambda(z_0)$ (Wieringa 1992)

Type of Surface	Roughness height z_0	$\lambda(z_0)$	Roughness Class
Sea, snow, sand	0.0005	0.14	I
Sea with very strong wind	0.005	0.15	II
Short grass	0.01	0.17	III
Cultivated open fields	0.05	0.19	IV
High plants, open country	0.10	0.20	V
Countryside and spread habitat	0.25	0.21	VI
Peripheral urban zone	0.50	0.22	VII
Mean city centre, forest	1.00	0.24	VIII
Metropolitan centre, tropical forest	4.00	0.25	IX

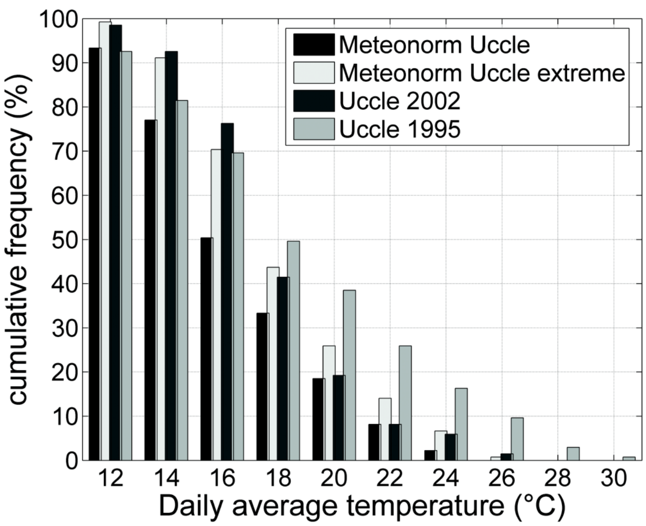

Figure 3 *Cumulative distribution of the daily average temperatures in extreme and typical weather data set and measurements.*

is reduced to the wind velocity on site at building height z $\bar{v}_z$ as follows (Allard and Alvarez, 1998):

$$\bar{v}_z = \lambda(z_0)\bar{v}_{ref}\ln\left(\frac{z}{z_0}\right)$$

This reduction depends on the roughness height z_0, an aerodynamic characteristic of the ground surfaces and thus a function of the nature of the ground and of the geometry of the existing obstacles, and the empirical coefficient $\lambda(z_0)$ (see Table 6). The choice of roughness class by the user in the input is the most important source of uncertainty in wind conversion. Therefore, a variation of 1 roughness class is assumed for the roughness class on site. The range of the roughness height z_0 for a building in an industrial zone is assumed [0.125 – 0.25 – 0.50], which approximately corresponds to variation of roughness classes V – VI – VII.

Table 7. Wind Pressure Coefficient *Cp* For a Building Surrounded by Obstructions Equivalent to Half the Height of the Building (Orme and Leksmono 2002)

Cp		Wind Direction (°) (Angle with Normal on Surface)							
		0	45	90	135	180	225	270	315
Façade	μ	0.25	0.06	–0.35	–0.60	–0.50	–0.6	–0.35	0.06
	σ	0.10							
Flat roof	μ	–0.60	–0.60	–0.60	–0.60	–0.60	–0.60	–0.60	–0.60
	σ	0.08							

Moreover, the wind pressure coefficient Cp calculates the local wind pressure on buildings from this wind velocity on-site. These Cp coefficients can be determined by wind tunnel experiments and CFD simulations. These methods are usually too expensive and time-consuming for building simulation. Therefore, the easier but less reliable methods of Cp generators (Knoll et al., 1995) and tables and figures (Orme and Leksmono, 2002), (ASHRAE, 2005) are used. They rely on interpolation or extrapolation of generic knowledge and previously measured data in wind tunnel studies and full-scale experiments. The use of these models is an important source of uncertainty. Therefore, the uncertainty on the Cp values is assumed as the difference between two successive classes in the simplified tables of Orme and Leksmono (2002) for low-rise buildings. This means a variation for the pressure coefficient on the façade and flat roof of respectively ± 0.2 and ± 0.15 (see Table 7). The Cp coefficients on a building and its variations are assumed to be correlated.

Simulations are carried out during the Belgian summer from May 21 to September 15 preceded by a 3-week dynamic start up. A time step of 15 min is chosen.

PRACTICAL GUIDELINES

The surplus of the results of the uncertainty and sensitivity analysis is the distribution of the thermal comfort. This distribution gives more reliable information on the predicted thermal comfort than the result of one single simulation. The disadvantage of this methodology is the huge computational cost. These analyses require a large amount of building simulations thus prevents building engineers from using uncertainty and sensitivity in the evaluation of the performances of natural night ventilation. Therefore, practical guidelines are developed. The methodology and the practical guidelines are both tested in the PROBE office building (Heijmans and Wouters, 2002). Temperature measurements confirm the predicted uncertainty on the level of thermal comfort. Moreover, the distribution of thermal comfort can be well predicted using the following practical guidelines (Breesch, 2006).

Prediction of Distribution

The range of the distribution is predicted based on three discrete simulations in which only the most important input parameters are varied. The list of most important parameters is the result of the sensitivity analysis in the general methodology, discussed in previous sections and summarized in Table 8. This result agrees rather well with the list of important factors influencing thermal comfort in a naturally ventilated office, determined by de Wit (2001).

The sets of input parameters for these three simulations are generally determined as follows:

- Average: average values for all input parameters
- Minimum: values smaller than the average for the most important parameters, average values for the remaining parameters
- Maximum: values larger than the average for the most important parameters, average values for the remaining parameters

Table 8. Most Important Parameters Influencing Thermal Comfort in Naturally Night Ventilated Office

No.	Parameter
1	Internal heat gains
2	Air tightness
3	Solar heat gain coefficient of sunblinds
4	Controlling sunblinds
5	Convective heat transfer coefficient
6	Wind pressure coefficient Cp
7	Controlling night ventilation (θ_i - θ_e)
8	Controlling night ventilation ($\theta_{s,ceiling}$)
9	$C_{d,opening}$
10	Thermophysical properties ($\lambda_{\text{internal brick}}$)
11	Thermophysical properties ($c_{\text{internal brick}}$)

The impact of the variation from the average value is studied in Figure 4 for a cross ventilated office on the south side. The impact for other orientations and strategies is similar. The input parameters equal to the average value decreased or increased by two times the standard deviation, i.e. $\mu \pm 2\sigma$, are noticed to overpredict distribution of the weighted temperature excess. A variation of one time the standard deviation from the average gives a better agreement with the results of the uncertainty analysis. In addition, Figure 5 discusses the impact of the amount of input parameters that are varied in these 3 simulations. Only varying the 5 most important parameters from Table 8 predicts the thermal comfort distribution rather well. No difference is noticed between the results when varying 9 or 11 input parameters. As a consequence, variations in the 9 most important parameters are taken into account in

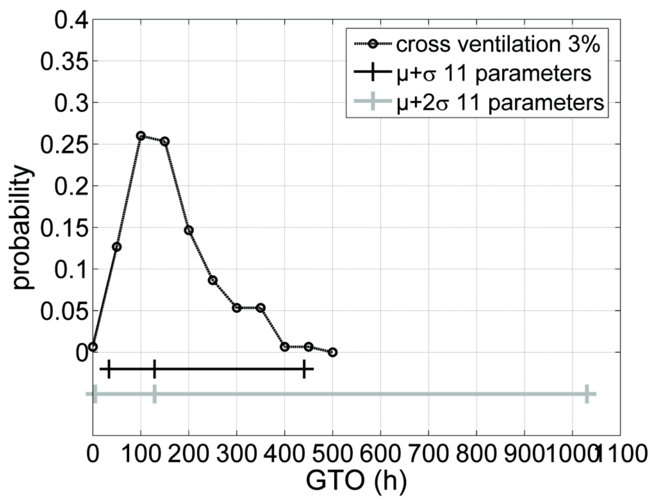

Figure 4 Impact of the variation on the input parameters on the predicted distributions.

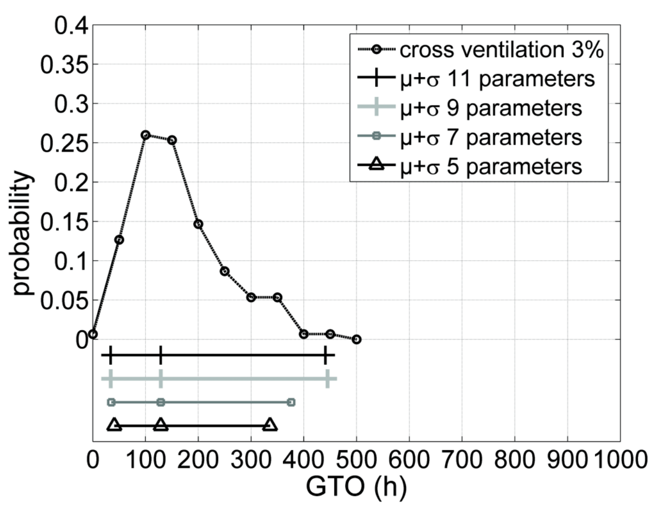

Figure 5 Impact of the amount of input parameters on the distributions.

the prediction of the distribution by 3 simulations. The results of these predictions for an office on the south side with respective single-sides, cross and stack night ventilation are shown in Figure 6. These predictions are added to the particular distribution as a line with 3 dots.

Weather Data

The performances of the design of natural night ventilation are evaluated using a typical and extremely warm weather data set in the simulations. These performances are characterized by the probability of good thermal comfort. This probability is calculated from the distribution of the weighted temperature excess hours (GTO), i.e. the probability that GTO is smaller than 150h. Figure 7 shows the impact of extremely warm weather data on the probability of good thermal comfort in a cross night ventilated office on the west side. The following variations on the base case are also described: top cooling, increased ventilation flow rate by day and extra thermal mass. Top cooling means that the ventilation flow rate by day is cooled down to the set point of night ventilation -6°C, i.e. 15.5 to 16.5, when the operative internal temperature exceeds the set point of night ventilation + 3°C, i.e. an indoor temperature between 24 and 25 °C. The ventilation capacity by day can be increased from 36 m^3/h.pers in the base case to 72 m^3/h.pers, a high indoor air quality according to EN 13779 (CEN, 2004b). Thermal mass is increased by providing heavy instead of light internal walls, that is, internal bricks instead of gypsum board. Figure 7 shows that the base case with one of these measures is a reliable design in normal weather conditions. These measures ensure a probability of good comfort larger than 0.9. Nevertheless, in extremely warm weather data, the probability of these measures decreases to approximately or lower than 0.6. Only when two of these measures are combined, a high probability of good thermal comfort is achieved during extremely warm outdoor temperatures, too.

CASE STUDY

The practical guidelines from the previous section are applied to evaluate the reliability of the design of natural night ventilation in the office building *Sint-Pietersnieuwstraat* of the Ghent University. This passive cooling method is preferred to mechanical cooling.

Building Characteristics

The *Sint-Pietersnieuwstraat* office building is located in the city center of Ghent (Belgium) and consists of two buildings separated by a courtyard that are part of a larger complex of offices, laboratories and an auditorium. Each building includes three office floors on top of a foyer and two underground service floors. The office building on the west side of the courtyard will be discussed. A 7-zone building model, including one office zone on the west and east side on each floor connected by a circulation zone, is created. A typical floor plan of this office building and the dimensions of the offices on the east and west side are shown in Figure 8. The height between floor and ceiling is 2.88m and between two floors, 3.91m. The total height of the office building is 18m.

The curtain wall façade of the offices is composed of sandwich (63%) and glass (37%) panes; the stairwell is completely finished with glass. The composition of the walls is shown in Table 9. A raised floor, exposed ceiling, light façade, light internal wall between the offices and a heavy internal wall between the offices and the corridor are provided. The transmittance coefficient U of glass equals 1.1 W/m^2K, the solar transmission coefficient 0.6. External sunblinds are provided on all windows with a g-value (glass included) of 0.15. These curtains are automatically controlled to be

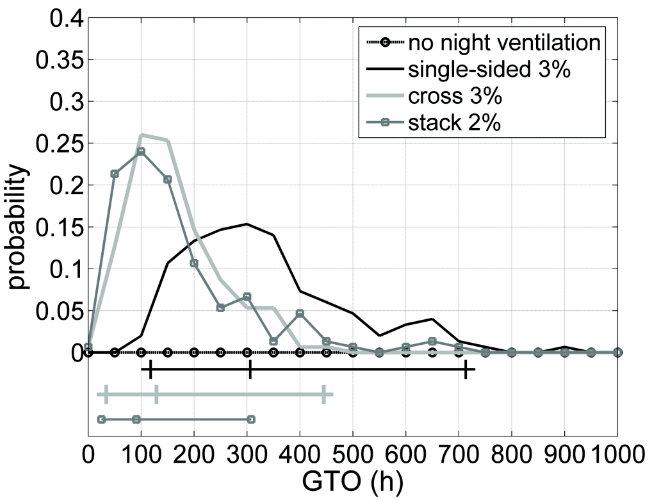

Figure 6 *Prediction of the distribution of GTO in an office on the south side.*

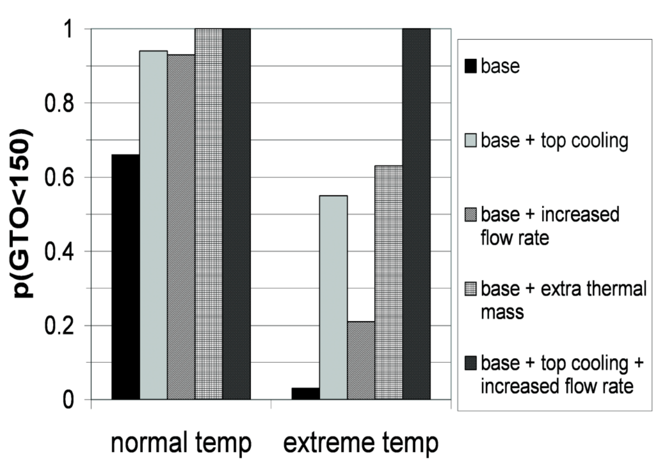

Figure 7 *Comparison of the probability of good thermal comfort between normal and extremely warm weather data in a cross night ventilated office on the west side.*

lowered from a solar radiation of 150 W/m^2. The offices are assumed to be occupied from Monday to Friday from 9:00 to 6:00. The design occupancy in the west and east office are approximately 12 m^2/pers. The total internal heat gains in the offices vary from 20.3 to 31.5 W/m^2, with an average of 25.1 W/m^2 of which 69% is convectively emitted. In the corridor, 6 W/m^2 of internal heat gains are assumed. The air tightness of the façade is characterized by an air mass flow coefficient C varying from 6 to 14*10^{-5} kg/(s.Pa^n.m^2) (Tamura and Shaw, 1976) and is modelled by cracks on the office floor and ceiling.

The wind pressure coefficients Cp are calculated in detail with the Cp generator of Knoll et al. (1995), based on a plan of the concerned building and its neighborhood in the city center. The variations are derived from Cp values calculated on various positions on the façade. For example, Figure 9 shows the variation of the wind pressure coefficient on the west façade. The roughness height z_0 on site is assumed 2m and varies from 1 to 4m.

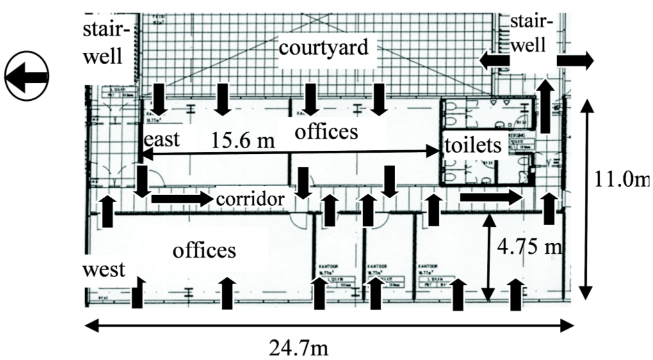

Figure 8 *Floor plan and design scheme natural night ventilation in the new office building "Sint-Pietersnieuwstraat" of the Ghent University (Belgium).*

The uncertainty intervals of the other building model characteristics are described in the section "Uncertainties on input parameters."

The scheme of natural ventilation by day and night in the *Sint-Pietersnieuwstraat* office building is shown in Figure 8. Outside air enters the offices through top-hung windows near the ceiling on each floor, flows to the corridor and leaves the building through outlet windows on top of the central stair-well. Figure 10 shows the height of these ventilation openings. Table 10 describes the effective area of the night and day ventilation openings. These openings are designed to ensure incoming flows on all floors according to the stack effect. The ventilation by day is designed to 30 m^2/h.pers, i.e. approximately 0.9 h^{-1}. This flow rate is increased to 2 h^{-1} when the indoor operative temperature exceeds 22°C. The designed

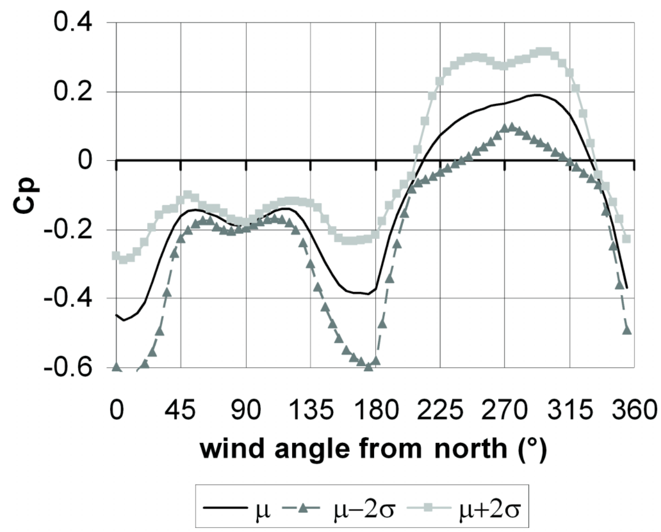

Figure 9 *Variation on the wind pressure coefficient Cp on the west side.*

Table 9. Wall Composition of the Office Building *Sint-Pietersnieuwstraat*

In between Ceiling/Floor		Roof		Façade	
Layer	d (cm)	Layer	d (cm)	Layer	d (cm)
Reinforced concrete	20	Reinforced concrete	20	Gypsum board	1
Light concrete	5	Insulation	12	Insulation	9
Air cavity	76	Bitumen	0.5	Aluminum	0.5
Plywood	1.8				
Carpet	0.4				
Light Internal Wall		**Heavy Internal Wall**			
Layer	d (cm)	Layer	d (cm)		
Gypsum board	1	Reinforced concrete	10		
Insulation	5				
Gypsum board	1				

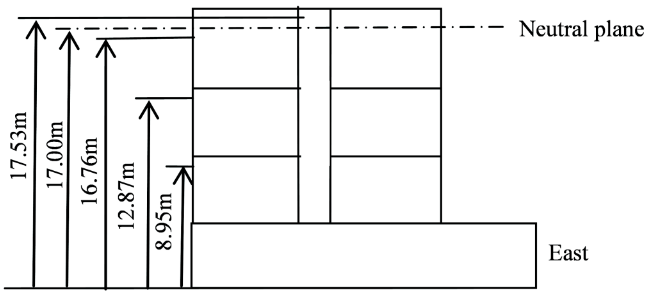

Figure 10 *Heights of supply and exhaust openings of natural ventilation, measured from the ground to the middle of the opening.*

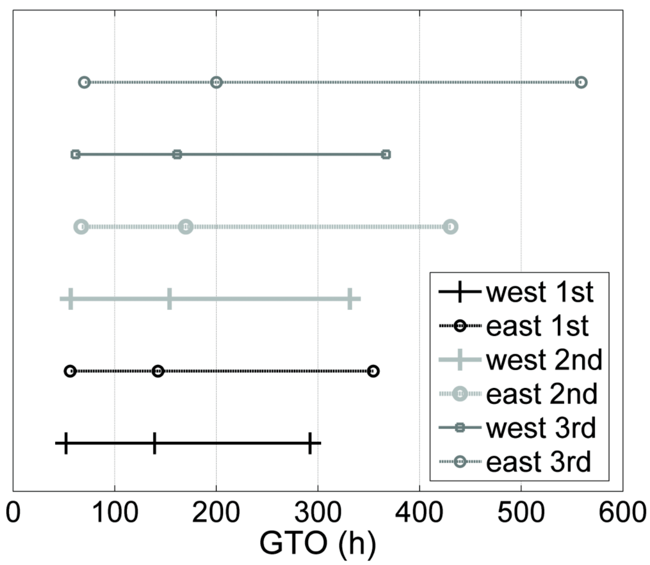

Figure 11 *Uncertainty intervals on GTO in Sint-Pietersnieuwstraat office building.*

area for night ventilation openings are small, compared to these in the generic building model.

Performance Evaluation

The practical guidelines from the previous section are applied to evaluate the reliability of the design of natural night ventilation in the *Sint-Pietersnieuwstraat* office building.

First, the distribution of thermal comfort in the offices of the *Sint-Pietersnieuwstraat* office building is estimated. These distributions are based on three discrete simulations in which only the nine most important input parameters of Table 8 are varied and shown in Figure 11. A moderate average thermal comfort is noticed in the office building *Sint-Pietersnieuwstraat*. However, a large variation in the weighted excess hours can be noticed in all offices. This is mainly caused by the predicted variation in internal heat gains in the offices. Moreover, the uncertainty is larger in the east than in the west office on the same floor due to the impact of the wind on the flow rates. Because the main wind direction in summer in Belgium

Table 10. Characteristics of Night and Hygienic Ventilation Openings

Floor	A_{eff}/A_{floor} (%) supply		
	By Day		By Night
	n = 0.9 h^{-1}	n = 2.0 h^{-1}	
First	0.08	0.17	0.27
Second	0.11	0.26	0.40
Third	0.47	1.05	1.89

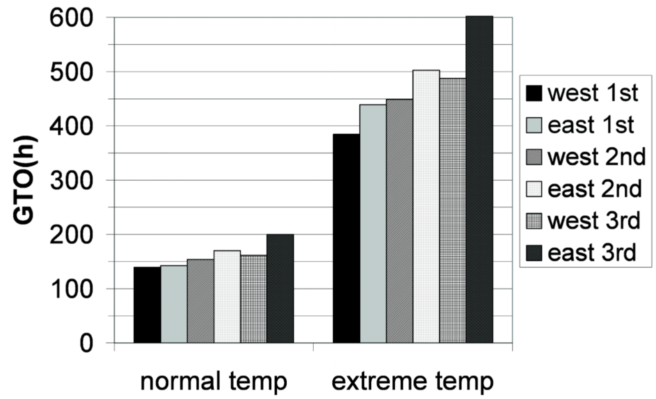

Figure 12 *Weighted temperature excess hours in normal and extremely warm weather.*

is south-west, an incoming ventilation flow is more probable on the west than on the east side. This impact is more obvious on the third floor where the wind velocity is higher and the wind pressure consequently exceeds the stack pressure more frequently than on the lower floors.

Second, the performances of the design of natural night ventilation are evaluated using a typical and extremely warm weather data set in the simulations. Figure 12 shows the weighted temperature excess hours using both weather data sets. Although an acceptable thermal comfort can be noticed in normal weather, none of the floors meet the criteria for good thermal comfort in extremely warm weather. The cooling capacity of the natural ventilation by day and night is significantly reduced.

DISCUSSION

A general methodology is developed to predict the performances of natural night ventilation using building simulation and taking into account the uncertainties in the input. To overcome the huge computational cost but ensure a reliable design, Breesch (2006) derived two practical guidelines from this general methodology. First, the range of the distribution of the performances is predicted based on three discrete simulations in which only the most important input parameters are varied. A variation of one times the standard deviation from the average of the 9 most important parameters is found. Figure 6 shows an excellent agreement between the uncertainty interval predicted by these three discrete simulations and the results of the Monte Carlo analysis for the different night ventilation strategies.

Second, to evaluate the performances of a natural night ventilation design properly, extremely warm weather data has to be taken into account. Figure 7 shows that in extremely warm weather data, the probability of good thermal comfort of an optimized design of natural night ventilation can be significantly reduced. Consequently, the combination of the standard and extremely warm weather data sets of Meteonorm Uccle is preferred to evaluate the performances of a natural night ventilation design.

These practical guidelines are used to evaluate the reliability of the design of natural night ventilation in the office building *Sint-Pietersnieuwstraat* of the Ghent University. Although acceptable thermal comfort can be noticed in normal weather conditions, none of the floors meets the criteria for good thermal comfort in extremely warm weather. A large distribution of thermal comfort can be noticed in normal weather. Consequently, it can be concluded that the design of natural night ventilation in the office building *Sint-Pietersnieuwstraat* cannot ensure reliable thermal comfort.

CONCLUSIONS

Building simulation is an appropriate tool to predict the performances of a natural night ventilation design. Nevertheless, the reliability of these simulation results depends on the accuracy of the input data. A methodology to predict the performances of natural night ventilation using building simulation to consider the uncertainties in the input is developed. The variation on the reached thermal comfort as well as the input parameters causing this uncertainty are determined because the distribution of thermal comfort gives more reliable information than the result of one single simulation.

Practical guidelines are derived from this general methodology to evaluate the reliability of a design of natural night ventilation. First, the distribution can be easily predicted, based on three discrete simulations in which only a list of the nine most important input parameters are varied. Second, to properly evaluate the performances of a natural night ventilation design, extremely warm weather data has to be taken into account. The combination of a normal and extremely warm weather data set is preferred.

The importance of these practical guidelines is shown in the evaluation of the reliability of the design of natural night ventilation in the office building *Sint-Pietersnieuwstraat*. The design of natural night ventilation in this office building cannot ensure reliable thermal comfort.

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