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Influence of design parameters on the night ventilation performance in office buildings based on sensitivity analysis

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ABSTRACT

Overheating and energy-extensive consumption in buildings, especially in office buildings, are emerging challenges. Night ventilation (NV) is a promising technique. The performance of NV can be evaluated by a series of performance indicators. As many design parameters affect those indicators, it is beneficial to choose suitable indicators and identify the most important design parameters to develop more efficient design solutions at the early design stage. Sensitivity analysis makes it possible to identify the most important design parameters in relation to NV performance and to focus design and optimization of NV on these fewer, but most important, parameters. A holistic approach integrating sensitivity analysis and parametric simulation analysis is developed to explore the key design parameters on night cooling performance indicators and evaluate the applicability and limitations of those indicators. The results show that the climatic conditions and NV modes strongly affect the influence of design parameters on the performance indicators. The window-wall ratio, internal thermal mass level, internal convective heat transfer coefficient, and night mechanical air change rate are the most important design parameters. The indicators of ventilative cooling advantage, cooling requirement reduction, and percentage outside the range are recommended for the night cooling performance evaluation.

1. Introduction

During the last decades, there has been a trend of increasing cooling demand in buildings. This has especially been the case for commercial buildings, where high internal loads in combination with high solar gains through extensive glazing have led to considerable cooling loads, even in moderate and cold climates (Artmann, Manz, & Heiselberg, 2008). An additional rise of the cooling demand is caused by global climate warming, which is expected to increase summertime temperatures significantly (Artmann, Gyalistras, Manz, & Heiselberg, 2008; Artmann, Manz, & Heiselberg, 2007). Night ventilation is a promising way to alleviate or solve the foregoing problem. The basic concept is to utilize the relatively low-temperature ambient air during the night time by the natural or mechanical ventilation systems to cool down the indoor air as well as the building construction components to provide a heat sink for the following day (Belmonte, Eguía, Molina, & Almendros-Ibáñez, 2015; Santamouris, Santamouris, & Asimakopoulos, 1996).

Numerous night cooling projects have been successfully undertaken in the past decades (Geros, Santamouris, Tsangrasoulis, & Guarracino, 1999; Ji et al., 2018; Solgi, Hamedani, Fernando, Skates, & Orji, 2018; Stritih et al., 2018; Wang, Yi, & Gao, 2009). Despite the simplicity of the concept, architects and engineers are hesitant to apply this low-energy technology (Breesch, Bossaer, & Janssens, 2005). One reason is that the efficiency of night-time cooling is affected by many parameters, which makes the performance predictions uncertain. Another reason is that there are many different performance indicators used for night ventilation design and evaluation, which confuse designers. Some of these indicators focus on temperature performance, others evaluate the energy balance, and several of them pay attention to thermal comfort. The heat removal effectiveness of night ventilation is evaluated by the temperature performance of the building and its relationship to the outdoor temperature profile. Several researchers have proposed different indicators for heat removal, including ventilation effectiveness for heat removal (Awbi & Gan, 1993), temperature efficiency (Artmann, Jensen, Manz, & Heiselberg, 2010), temperature difference ratio (Givoni, 1992), decrement factor, and daily time lag (Gagliano, Patania, Nocera, & Signorello, 2014). The energy efficiency of night ventilation is evaluated by the ratio of ventilation energy saving and ventilation equipment energy use. The indicators for energy efficiency proposed by researchers are the coefficient of performance (Pfafferott, Herkel, & Jäschke, 2003), potential energy efficiency index (Blondeau, Spérandio, & Allard, 1997), ventilative cooling advantage, cooling requirement reduction (O'Donnavan et al., 2018), etc. For thermal comfort evaluation when applying night ventilation, there are indicators like the

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Nomenclature

T_{out}	Outlet air temperature (°C)
T_{in}	Inlet air temperature (°C)
$\bar{T}_{surface}$	Average building indoor surface temperature (°C)
$T_{o,max}$	Maximum ambient air temperature (°C)
T_{o},*min*	Minimum ambient air temperature (°C)
$T_{i,max}$	Maximum building indoor air temperature (°C)
$T_{i,max}$	Minimum building indoor air temperature (°C)
$T_i(t)$	Building indoor air temperature at time t (°C)
$T_o(t)$	Ambient air temperature at time t (°C)
$\dot{m}_{air}$	Airflow rate (kg/s)
c_p	Specific heat capacity (kJ/kg.°C)
P_e	Electric power of fan (W)
t_i	Start time of night-time ventilation (h)
t_f	End time of night-time ventilation (h)
$Q_{el,c}^{ref}$	Cooling system electrical energy consumption of the scenario without ventilative cooling (kWh/m^2)
$Q_{el,c}^{scen}$	Cooling system electrical energy consumption of the scenario with ventilative cooling (kWh/m^2)
$Q_{el,v}$	Electrical energy use of the night ventilation system
$Q_{t,c}^{ref}$	Cooling demand of the reference scenario (kWh)
$Q_{t,c}^{scen}$	Cooling demand of the analyzed scenario (kWh)
wf_i	Weighting factor
h_i	Occupied hours (h)
$T_{comf,sup}$	Upper comfort temperature limit (°C)

Abbreviations

NV	Night ventilation
TE	Temperature efficiency
TDR	Temperature difference ratio
DF	Decrement factor
COP	Coefficient of performance
ADV	Ventilative cooling advantage
CRR	Cooling requirements reduction
POR	Percentage outside the range
DhC	Degree-hours criterion
DI	Weighted discomfort temperature index
SHGC	Solar heat gain coefficient
CHTC	Convective heat transfer coefficient
MCA	Monte Carlo analysis
LHS	Latin hypercube sampling
SRC	Standardized regression coefficient
SA	Sensitivity analysis
ACH	Air change rate per hour
WWR	Window-wall ratio
AC	Air conditioner

degree-hours criterion (Artmann, Manz et al., 2008) and the weighted discomfort temperature index (Corgnati & Kindinis, 2007). Some of the indicators are independent of each other, others have a different level of dependency between each other. It is necessary to choose multiple indicators to have an overall evaluation of the night ventilation performance.

Sensitivity analysis is a useful tool to identify the most important parameters for the building design and energy analysis (Tian, 2013). The methods for sensitivity analysis can be sorted into local sensitivity methods and global sensitivity methods (Saltelli, Ratto, Tarantola, & Campolongo, 2005). Local sensitivity analysis is based on only varying one design parameter at a time, while the global sensitivity analysis is based on changing all the design parameters at the same time (Mara & Tarantola, 2008). Therefore, the global method is more reliable but with a high computational calculation effort compared to the local method. Both local (Firth, Lomas, & Wright, 2010; Lam, Wan, & Yang, 2008; Lomas & Eppel, 1992; Petersen & Svendsen, 2010) and global methods (Breesch & Janssens, 2010; Goethals, Breesch, & Janssens, 2011; Heiselberg et al., 2009; Hopfe & Hensen, 2011; Hygh, DeCarolis, Hill, & Ranji Ranjithan, 2012) have been widely used in investigating the most important variables related to building energy performance. Among those, few research are about night ventilation performance. Artmann, Manz et al. (2008) conducted a local sensitivity analysis to investigate the most influential design parameters for night mechanical ventilation in an office room located in a moderate climatic location with the indicator of the number of overheat degree hours. The conclusion was that the climatic conditions and air flow rate at night-time were the most important parameters. Finn, Connolly, and Kenny (2007) examined the design and operational parameters in a night ventilated library building located in a maritime type climate. The result showed the building mass as the most significant parameter, followed by the internal heat gains and night air flow rates. Breesch and Janssens (2010), Breesch, Janssens, and Gameiro Da Silva (2004) analyzed the input parameters causing the uncertainty on the thermal comfort for a single-sided night natural ventilation in the moderate climate. The results showed that the top 3 important design parameters were the internal heat gains, the solar heat gain coefficient of the sun blinds, and the internal convective heat transfer coefficient. Encinas and De Herde (2013) found that for night cooling of a real estate market in a warm climate region, the most important input parameter for summer comfort is solar and light transmittance of the solar protection devices, followed by the night ventilation flow rate. Goethals et al. (2011) investigated the sensitivity of convection algorithms on the night ventilation performance, showing that the selection of the convection algorithm strongly affects the energy and thermal comfort predictions. Ran and Tang (2018) adopted the local sensitivity analysis method to investigate the influence of external wall insulation level, night ventilation airflow rate on the indoor air temperature reduction, showing that the increase of the insulation level and night airflow rate will enhance the night cooling performance.

The aforementioned sensitivity analyses for night ventilation performance are mostly only focused on one night ventilation mode with one daytime cooling method or limited to the amount of performance indicators and climate regions. To get an overall design guideline of night ventilation design parameters, research should include various night ventilation systems and performance indicators in different climatic conditions.

This paper firstly selects nine performance indicators for night ventilation performance evaluation. Then it investigates the performance of night mechanical and natural ventilation integrated with three different daytime cooling systems (air conditioning, mechanical ventilation, and natural ventilation) to do a global sensitivity analysis for an office room located in three climate zones (cold, medium, and hot climate regions). The night cooling performance is analyzed based on the parametric simulation results in consideration of the thermal comfort evaluation and energy-saving benefit. Finally, the evaluation of the applicability of performance indicators is conducted to propose the recommendation.

2. Methodology

2.1. Outline of the quantitative study

A systematic approach is proposed to evaluate and quantify the influence of different design parameters on the night ventilation performance alongside the evaluation of performance indicators as shown in Fig. 1. *In the first step*, a suitable series of performance indicators for night cooling are reviewed and selected. *In the second step*, a software designed for uncertainty and sensitivity analysis by Monte Carlo method-SimLab v2.2 (EU Science Hub, 2008) generates samples based on the input design parameters and sends the scenarios to the parametric simulation manger jEPlus (Zhang & Korolija, 2016). Then, the jEplus uses the model built by EnergyPlus to do parametric simulations before transferring the simulation results back again to SimLab. Follow on, a global sensitivity analysis is conducted in SimLab by regression method to investigate the influence of design parameters on performance indicators. Finally, the parametric simulation results of night cooling performance indicators are used to propose the application recommendations for those performance indicators by mathematical analysis.

2.2. *Performance indicators of night ventilation*

Appropriate performance indicators should be chosen according to the application conditions of the night ventilation, in order to provide guidelines for the measurement or simulation in the design process to achieve those goals. It should be noted that the performance of night ventilation cannot be well represented by a single indicator. It needs a combination of different types of indicators. The performance of night ventilation can be quantified by the thermodynamical effect (energy balance) and by its cooling effect (room temperature). Night ventilation performance indicators can be sorted into the following four categories: 1) Heat removal effectiveness, 2) Energy efficiency, 3) Ability to reduce cooling energy use, and 4) Thermal comfort improvement (Rui, Yue, & Heiselberg, 2018). Heat removal effectiveness quantifies the ability of the night cooling system to remove excess heat stored in the building. Energy efficiency quantifies the energy use required to reduce cooling demand. The ability to reduce cooling energy use represents the ability of the night cooling system to provide energy saving for the daytime mechanical cooling. Thermal comfort improvement shows the ability of the night cooling system to reduce periods of thermal discomfort during the occupied time.

Some indicators are more suitable for simulation analysis because they can be easily calculated by post-processing outcomes of building energy simulation runs of a reference scenario (e.g. mechanically cooled building) and a ventilative cooling scenario (e.g. natural night cooling and daytime mechanical cooling). However, other indicators are more suitable for experimental analysis, since some data is easier to obtain in field studies. In addition, in experimental studies, the thermal comfort improvement indicators are much more prevalent than the energy efficiency indicators, probably because the indoor conditions are easier obtained than energy data, which is often challenging to measure directly.

In this paper, we select nine performance indicators in total from the four categories mentioned above to evaluate the influences of different design parameters. Table 1 summarizes the selected performance indicators.

2.3. *Case study*

2.3.1. *Building model*

The EnergyPlus v.8.9 software was selected in this study to build a model and simulate its heat, energy, and thermal comfort performance. An office building located in Aarhus, Denmark was used for this study, as shown in Fig. 2(a). The building is 103.7 m long and 9.5 m wide, with 3 stories and a total area of 2924.1 m^2. The layout of the office building can be seen in Fig. 2(b), in which N, W, S, and C indicate the orientation as north, west, south, and center respectively. A typical office room 1 W occupied by 6 persons was selected as the case zone, whose floor area is 51.3 m^2 and height is 2.8 m (Vidrih, Arkar, & Medved, 2016). Internal partitions between the concerned zone 1 W and adjacent zones were set as adiabatic to assume the similar conditions in all adjacent zones. The case was simulated in the hot (Rome), medium (Geneva), and cold (Copenhagen) climates respectively to investigate the climate influence on night ventilation performance. The weather data for the three locations originated from the World Meteorological Organization (WMO, 2018).

In order to evaluate the influence of building orientation on night ventilation performance, the orientation was set with a uniform distribution from 0° to 360°. The European ventilation standard for office building recommends that the airtightness should be below 1.0 h^{-1} in case of buildings with more than three stories (EN 16798-3, 2017). The infiltration of building airtightness was set with triangular distribution with a minimum value of 0.1 h^{-1}, maximum 1.0 h^{-1}, and mean value 0.6 h^{-1}.

2.3.2. *Thermal mass models*

Thermal mass can be sorted as external and internal thermal mass. External thermal mass, such as an external wall or roof, is affected by the ambient air temperature and solar radiation directly. Internal thermal mass, such as internal walls or interior furniture, influences the indoor air temperature through the process of absorbing and releasing heat (Zhou, Zhang, Lin, & Li, 2008). For the concerned zone 1 W, the external thermal mass is the external wall, while the internal thermal mass contains an internal wall, ceiling, floor, and interior furniture.

Three different levels (light, medium, heavy) were defined for

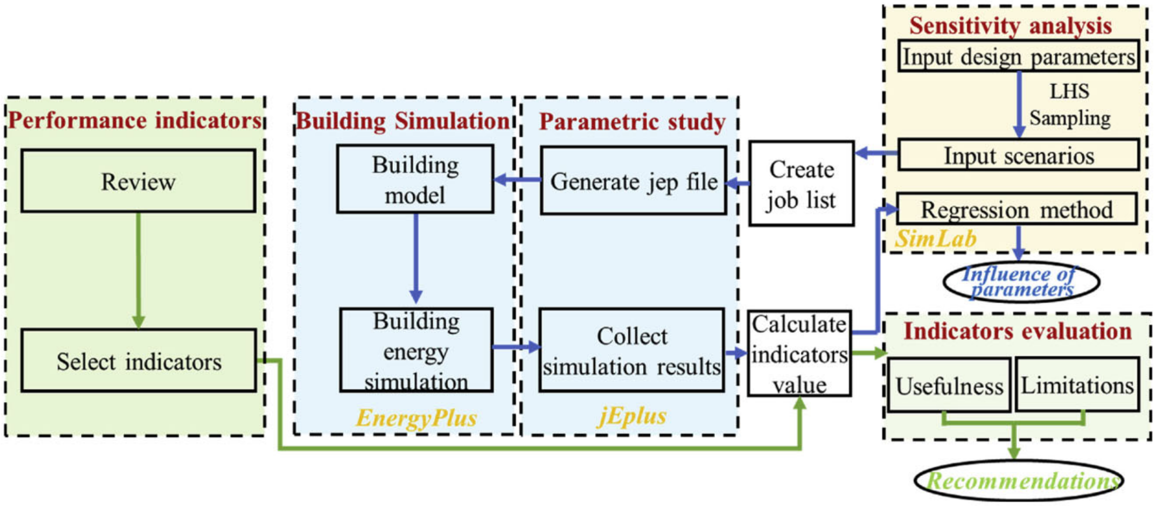

Fig. 1. Flow chart of the systematic approach.

Table 1
Summary of the selected performance indicators.

Family of indices	Indicator name	Expression	Explanation	Source
Heat removal effectiveness	Temperature efficiency (TE)	$TE = \frac{T_{out} - T_{in}}{\bar{T}_{surface} - T_{in}}$	Originates from experimental studies. Mainly depends on the air distribution concept and the airflow rate. For mixing ventilation, the value of temperature efficiency is limited to 1, while in displacement ventilation the temperature stratification can result in an efficiency exceeding 1.	(Artmann et al., 2010)
	Temperature difference ratio (TDR)	$TDR = \frac{T_{o,max} - T_{i,max}}{T_{o,max} - T_{o,min}}$	Used with good results to compare passive cooling systems with different configurations. A higher value of TDR indicates a larger temperature difference between indoors and outdoors and thus a more efficient night cooling strategy.	(Givoni, 1992)
	Decrement factor (DF)	$DF = \frac{T_{i,max} - T_{i,min}}{T_{o,max} - T_{o,min}}$	Means the ratio of indoor air temperature fluctuation to the ambient air temperature fluctuation.	(Gagliano et al., 2014)
Energy efficiency	Coefficient of performance (COP)	$COP = \frac{\int_{t_s}^{t_e} \dot{m}_{air} c_p (T_i(t) - T_o(t))dt}{\int_{t_s}^{t_e} P_e(t)dt}$	The ratio of the cooling energy delivered into the building to the auxiliary electric consumption by mechanical machines during the night period. The higher the COP, the better the performance for night-time ventilation.	(Pfafferott et al., 2003)
	Ventilative cooling advantage (ADV)	$ADV_{VC} = \frac{Q_{el,c}^{ref} - Q_{el,c}^{scen}}{Q_{el,v}}$	Defines the benefit of the night ventilative cooling in case which ventilation rates are provided mechanically. If ADV_{VC} is lower than 1, the electrical energy use of the scenario is higher than the reference scenario. If ADV_{VC} is higher than 1, the electrical energy use of the scenario is lower than the reference scenario.	(O'Donnavan et al., 2018)
Ability to reduce cooling energy use	Cooling requirements reduction (CRR)	$CRR = \frac{Q_{t,c}^{ref} - Q_{t,c}^{scen}}{Q_{t,c}^{ref}}$	Expresses the percentage of reduction of the cooling demand of a scenario with night cooling in respect to the cooling demand of the reference scenario. The value of CRR can range between -1 and +1. If CRR is positive, it means that the night ventilative cooling system reduces the cooling need of the building. If the value of CRR is negative or 0, it means that the night ventilative cooling system does not reduce the cooling requirements	(O'Donnavan et al., 2018)
Thermal comfort improvement in daytime	Percentage outside the range (POR)	$POR = \frac{\sum_{t=1}^{Oh} (wf_i \cdot h_i)}{\sum_{t=1}^{Oh} (h_i)}$	Accumulate the percentage of occupied hours when the thermal comfort parameters are outside a specified range. The comfort range can be expressed in terms of PMV when referring to the Fanger model or in terms of operative temperature when referring to the adaptive comfort model. If the thermal comfort parameters exceed the corresponding comfort range, the wf_i would be 1, or the wf_i would be 0. The lower value of POR is, the better thermal comfort improvement is provided by night ventilative cooling.	(Carlucci & Pagliano, 2012)
	Degree-hours criterion (DhC)	$DhC = \sum_{t=1}^{Oh} (wf_i \bullet h_i)$	Accumulate overheating degree hours of the operative room temperature above 26℃ during the occupied period. wf_i here is calculated as the module of the difference between actual and calculated operative temperature. The lower the value of DhC is, the better the thermal comfort improvement is provided by night ventilation.	(Artmann, Manz et al., 2008)
	Weighted discomfort temperature index (DI)	$DI = \sum (T_i - T_{comf,sup})$	Discomfort weighted on the distance of calculated operative temperature from the comfort temperature upper limit which is fixed at 28 °C. The lower the value of DI is, the better thermal comfort improvement is provided by night ventilation.	(Corgnati & Kindinis, 2007)

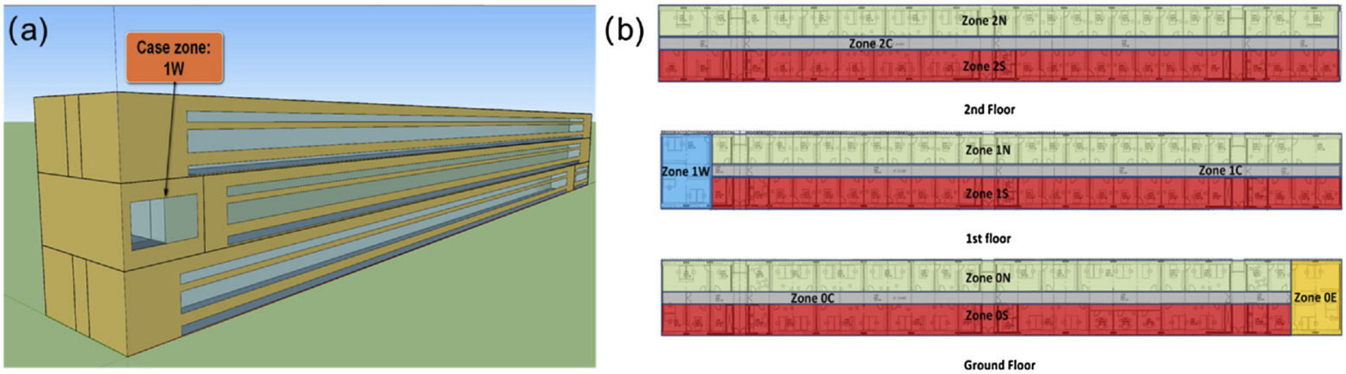

Fig. 2. (a) View of the building model and (b) Layout of the case office building.

external and internal thermal mass, respectively. Table 2 shows the detailed composition of the thermophysical properties of building materials and the thermal mass of the building components. The last column of Table 2 is the dynamic heat capacity per unit floor area, indicating the thermal mass level. The dynamic heat capacity c_{dyn} is the ability to store energy per area when the building component is exposed to a sinusoidal temperature variation for a period of 24 h with surface resistance, as defined by EN ISO (13786, 2017). It should be noticed that for light, medium, and heavy internal thermal mass levels, the interior furniture surface area is 10, 30, 50 m^2 respectively.

2.3.3. Internal heat gain models

Similar to the thermal mass, internal heat gains were also defined by three different levels, cf. Table 3. The hourly operational schedules for people, lights, and electric equipment were always 1.0 during the occupied hours (08:00–17:00) and 0 for the other hours. The people clothing insulation was set to 0.5 clo in summer (EN 15251, 2007).

2.3.4. Window models

The windows in zone 1 W were modeled as energy-efficient windows with a double pane construction made by 3 mm glass and a 13 mm gap filled with argon. The window U-value is 1.062 $W/m^2{\cdot}K$, while the glass solar heat gain coefficient (SHGC) and visible transmittance are 0.579 and 0.698 respectively. In order to evaluate the influence of window-wall ratio on night ventilation performance, the design parameter of the window-wall ratio for north and south windows of zone 1 W was set with a discrete distribution from 10%, 20%,..., 90%.

2.3.5. Night ventilation systems

Two typical concepts of night ventilation were selected for the investigation, which are mechanical ventilation and natural ventilation. The night venting schedule is during 17:00-08:00 (+1) from 1st July to 1st September, except for weekends.

The night mechanical ventilation system is a balanced system with a supply fan and an exhaust fan. The night natural ventilation has been modeled using a wind and stack model in EnergyPlus, in which the ventilation air flow rate is a function of wind speed and thermal stack effect, along with the area of the opening being modeled (U. Department of Energy, 2017).

To prevent the overcooling and to store more cooling energy in building thermal mass, the minimum indoor air temperature setpoint for both night ventilation systems was 18℃ (M.A. J, 1995). Night ventilation is only activated when the indoor air temperature exceeds the ambient temperature at a certain temperature which was set with a discrete value of 1, 2, and 3 ℃.

Because the maximum airflow rate for the design of night ventilation should be further increased corresponding to an air change rate of 10 h^{-1} (O'Donnavan et al., 2018), the design air flow rate for night mechanical ventilation was set with uniform distribution from 1 to 10 h^{-1}. For night natural ventilation, the opening area is 0.4 m^2, and the discharge coefficient of the opening was set with a typical uniform distribution from 0.5 to 0.7 (Flourentzou, Van der Maas, & Roulet, 2002). The opening effectiveness for natural ventilation was calculated automatically in EnergyPlus so that the window can be assumed to adjust its angle to make the most use of wind under different wind direction. Table 4 shows the detailed setup information of night ventilation.

2.3.6. Daytime cooling systems

Three typical methods were selected to cool the building at daytime, which are air conditioner (AC), mechanical ventilation, and natural ventilation. The operating period for daytime cooling is 08:00–17:00 on weekdays from 1st July to 1st September.

A packaged thermal heat pump with a dedicated outdoor air system was modeled as the air conditioning system with COP (coefficient of performance) 3.0 for cooling in summer with the HVAC template module of EnergyPlus. The setpoint for the air conditioning system is 24.5℃ which is a middle point of the temperature range for cooling, EN 15251 (EN 15251, 2007). The outdoor air flow rate was set to 30 m^3/h per person (EN 15251, 2007).

The setups for daytime mechanical ventilation and natural ventilation are similar to that of night mechanical and natural ventilation systems respectively, but with some differences. The first difference is the design flow rate for daytime mechanical ventilation and maximum flow rate for daytime natural ventilation is 6 h^{-1}. It is because the typical maximum air flow rate used in the design of daytime ventilative cooling is 6 h^{-1} (O'Donnavan et al., 2018). The second difference is that when the indoor and outdoor air temperature difference is smaller than 2°C, the outdoor air flow rate is 30 m^3/h per person to fulfill the human hygiene requirements. Table 5 shows the detailed setup information of daytime cooling methods.

2.3.7. Internal convective heat transfer coefficient

Several research indicated different convective heat transfer coefficient (CHTC) correlations or values for different types of the internal surface (Alamdari & Hammond, 1983; Lomas, 1996). According to the EN ISO (13791, 2012), the standard convective heat transfer coefficient for vertical, horizontal (upward), and horizontal(downward) are 2.5, 5.0, 0.7 $W/m^2{\cdot}K$ respectively. As a consequence, the CHTC of internal surfaces were both set with uniform distribution from 0.5 to 5 $W/m^2{\cdot}K$.

2.3.8. Summary of the independent design parameters

Table 6 summarizes the independent design parameters for night mechanical/natural ventilation. P6 has two meanings, of which night air change rate per hour (ACH) is for mechanical ventilation and discharge coefficient for the opening of natural ventilation.

2.4. Sensitivity analysis

Sensitivity analysis (SA) can be divided into three different types:

Table 2
Detailed composition of the thermal mass and thermophysical properties of building materials.

External thermal mass

	d (mm)	ρ (kg/m^3)	c (J/kg/K)	λ (W/m·K)	Total c_{dyn}/A_{floor} (kJ/m^2·K)
External wall (Heavy)					
Plaster	15	1400	936	0.7	
Sand-lime	150	2000	936	1.1	
Exp.polystyrene	120	40	1200	0.035	
Plaster ext.	20	1600	1000	0.87	77.5
External wall (Medium)					
Plasterboard (fire-resisting)	160	900	1000	0.25	
Concrete 200	200	2385	800	1.2	
PUR 210	210	40	1400	0.021	
Cement plate	15	2000	1500	0.35	42.0
External wall (Light)					
Gpysum board	25	1000	792	0.4	
Exp.polystyrene	120	40	1200	0.035	
Concrete 180	180	2400	1080	1.8	24.0

Internal thermal mass

	d (mm)	ρ (kg/m^3)	c (J/kg/K)	λ (W/m·K)	$R_{userdefined}$ (m^2·K/W)	Total c_{dyn}/A_{floor} (kJ/m^2·K)
Internal wall (heavy)						
Plaster	15	1400	936	0.7		
Sand-lime	150	2000	936	1.1		
Plaster	15	1400	936	0.7		
Ceiling (Heavy)						
Concrete 180	180	2400	1080	1.8		
Floor (Heavy)						
Concrete 180	180	2400	1080	1.8		
Sound insulation	40	30	1404	0.04		
Plaster floor	80	2200	1080	1.5		
Carpet	5	80	930	0.05		
Interior furniture (Heavy)						
Wood 6inch	150	540	1210	0.12		238.1
Internal wall (Medium)						
Gypsum board	25	1000	792	0.4		
Mineral wool	70	1750	1000	0.56		
Gypsum board	25	1000	792	0.4		
Ceiling (Medium)						
Cast concrete	120	1800	1000	1.13		
Floor (Medium)						
Linoleum	3	1200	1470	0.17		
Cement screed (fiber reinforced)	50	1400	1000	0.8		
Acoustic insulation	9	556	1700	0.15		
OSB panels	25	600	2150	0.13		
Insulation glass wool	200	28	1030	0.032		
Wooden panels	60	250	2100	0.047		
Interior furniture (Medium)						
Wood 6inch	150	540	1210	0.12		160.1
Internal wall (Light)						
Gypsum board	25	1000	792	0.4		
Mineral wool	70	90	612	0.036		

(continued on next page)

Table 2 (*continued*)

Internal thermal mass	*d* (mm)	ρ (kg/m^3)	*c* (J/kg/K)	λ (W/m·K)	$R_{userdefined}$ (m^{2}K/W)	Total c_{dyn}/A_{floor} (kJ/m^{2}K)
Gypsum board	25	1000	792	0.4		
Suspend ceiling (Light)						
Acoustic panel	20	800	900	0.21		
Air gap	250				0.16	
Floor (Light)						
Linoleum	3	1200	1470	0.17		
Acoustic insulation	9	556	1700	0.15		
OSB panels	25	600	2150	0.13		
Insulation glass wool	200	28	1030	0.032		
Wooden panels	60	250	2100	0.047		
Interior furniture (Light)						
Wood 6inch	150	540	1210	0.12		63.3

Table 3
Internal heat gains per unit floor area in zone 1 W.

Internal heat gains		Low	Medium	High
People	W/pers.	70	75	80
Lights	W/m^2	4	6	8
Electric equipment	W/m^2	6	8	10
Total	W/m^2	18.2	22.8	27.4

Table 4
Detailed setup information of night ventilation systems.

Night mechanical ventilation	
System	Supply fan + exhaust fan
Design pressure rise	600 Pa (Both for supply and exhaust fan)
Fan total efficiency	0.9
Design flow rate	**U**[1-10]
Minimum indoor temperature	18℃
Activation requirements	T_{in}-T_{out} > **D**[1,2,3]℃
Night natural ventilation	
System	Natural ventilation driven by wind and stack effect
Minimum indoor temperature	18 ℃
Activation requirements	T_{in}-T_{out} > **D**[1,2,3]℃
Opening area	0.4 m^2
Discharge coefficient	**U**[0.5-0.7]
Opening effectiveness	Automatic calculation by EnergyPlus

T_{in}: indoor air temperature (℃); T_{out}: ambient temperature (℃); D: discrete distribution (levels); U: uniform distribution (lower value, upper value).

Table 5
Detailed setup information about daytime cooling methods.

Daytime air conditioning	
System	Packaged terminal heat pump + dedicated outdoor air system
Setpoint	24.5 ℃
Design fan pressure rise	75 Pa
Outdoor air flow rate	30 m^3/h/person
Daytime mechanical ventilation	
System	Supply fan + exhaust fan
Design fan pressure rise	1000 Pa (Both for supply and exhaust fan)
Fan total efficiency	0.9
Minimum indoor temperature	24.5 ℃
Design flow rate	6 h^{-1} or 30 m^3/h/person
Control strategy	If T_{in}-T_{out} > 2 ℃ air flow = 6 h^{-1} or flow = 30 m^3/h /person
Daytime natural ventilation	
System	Natural ventilation driven by wind and stack effect
Minimum indoor temperature	24.5 ℃
Opening area	0.4 m^2
Discharge coefficient	**U**[0.5–0.7]
Control strategy	If T_{in}-T_{out} > 2℃ air flow < 6 ACH or flow = 30 m^3/h /person
Opening effectiveness	Automatic calculation by EnergyPlus

screening methods, local sensitivity methods, and global sensitivity methods (Saltelli, Chan, & Scott, 2000). In this paper, the global sensitivity analysis methods were selected to quantify the influence of a single input variable on the outputs while all other input variables also vary simultaneously. Monte Carlo Analysis (MCA) is the most prevalent variance-based method because it provides approximate solutions only with a restricted number of simulations and the input variables have uncertainties of a different order of magnitude (Breesch & Janssens, 2010). Different sampling methods exist in MCA studies: random sampling, importance sampling, quasi-random sampling, and Latin hypercube sampling (LHS). The LHS method was selected because this method is a powerful tool in building performance analysis and it fully covers the range of each variable (Tian, 2013). The sample size based on LHS was chosen to be 400 as the minimum number of model

Table 6
Design parameters for sensitivity analysis, their range, and distribution.

Parameter		Unit	Distribution
P1	External thermal mass	kJ/m²·K	**D**[24.0, 42.0, 77.5]
P2	Internal thermal mass	kJ/m²·K	**D**[63.3, 160.1, 238.1]
P3	Internal heat gains	W/m²	**D**[18.2, 22.8, 27.4]
P4	Window-wall ratio (WWR)	%	**D**[10, 20, 30, 40, 50, 60, 70, 80, 90]
P5	Internal CHTC	W/m²·K	**U**[0.7-5]
P6	Night ACH	h⁻¹	**U**[1-10]
	Discharge coefficient for opening	–	**U**[0.5-0.7]
P7	Building airtightness	h⁻¹	**T**[0.1, 0.6, 1]
P8	Building orientation	°	**U**[0-360]
P9	Indoor and outdoor ΔT	°C	**D**[1,2,3]

Note: D: discrete distribution (levels); U: uniform distribution (lower value, upper value); T: triangular distribution (lower value, mode, upper value).

executions should be higher than 10 times the number of variables (European Commission - IPSC, 2008). SimLab v2.2 generated the 400 samples by LHS method (European Commission - IPSC, 2008), then those samples were sent to jEPlus to do parametric simulations before transferring the simulation results back again to SimLab to do the sensitivity analysis. The Standardized Regression Coefficient (SRC) based on regression analysis was used as the global sensitivity analysis indicator when the input variables are independent. The sign of SRC indicates whether the output increases (positive value) or decreases (negative value) with the related input variable increases. The bigger the absolute value of SRC, the more influential the input variable is. Calculating the SRCs involves a linear multidimensional model based on an $m \times k$ samples, with m the total number of samples and k the total number of input variables:

$$\hat{y}_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_j \tag{1}$$

where $\hat{y}_i$ represents the estimate of the output y_i, x_j the input variable, i is the sample size, j is the number of variables and β_j the regression coefficient. This regression model can be standardized by subtracting the mean value from each input and output factor and successively dividing this result by its standard deviation:

$$\frac{\hat{y}_i - \bar{y}}{\hat{\sigma}} = \sum_{j=1}^{k} \frac{\beta_j \hat{\sigma}_j}{\hat{\sigma}} \frac{(x_j - \bar{x}_j)}{\hat{\sigma}_j}$$

where

$$\bar{y} = \sum_{i=1}^{m} \frac{y_i}{m},\ \bar{x}_j = \sum_{i=1}^{m} \frac{x_{ij}}{m},\ \hat{\sigma} = \sqrt{\left[\sum_{i=1}^{m} \frac{(y_i - \bar{y})^2}{m-1}\right]},\ \hat{\sigma}_j = \sqrt{\left[\sum_{i=1}^{m} \frac{(x_{ij} - \bar{x}_j)^2}{m-1}\right]} \tag{2}$$

The SRC for the input variable j is defined as:

$$SRC_j = \frac{\beta_j \hat{\sigma}_j}{\hat{\sigma}} \tag{3}$$

The model coefficient of determination R_y^2 measures how well the linear regression model matches the data, which can be calculated by:

$$R_y^2 = \frac{\sum_{i=1}^{m} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{m} (y_i - \bar{y})^2} \tag{4}$$

where R_y^2 represents the fraction of the variance of the output explained by the regression. The closer it is to 1, the better the model performance is.

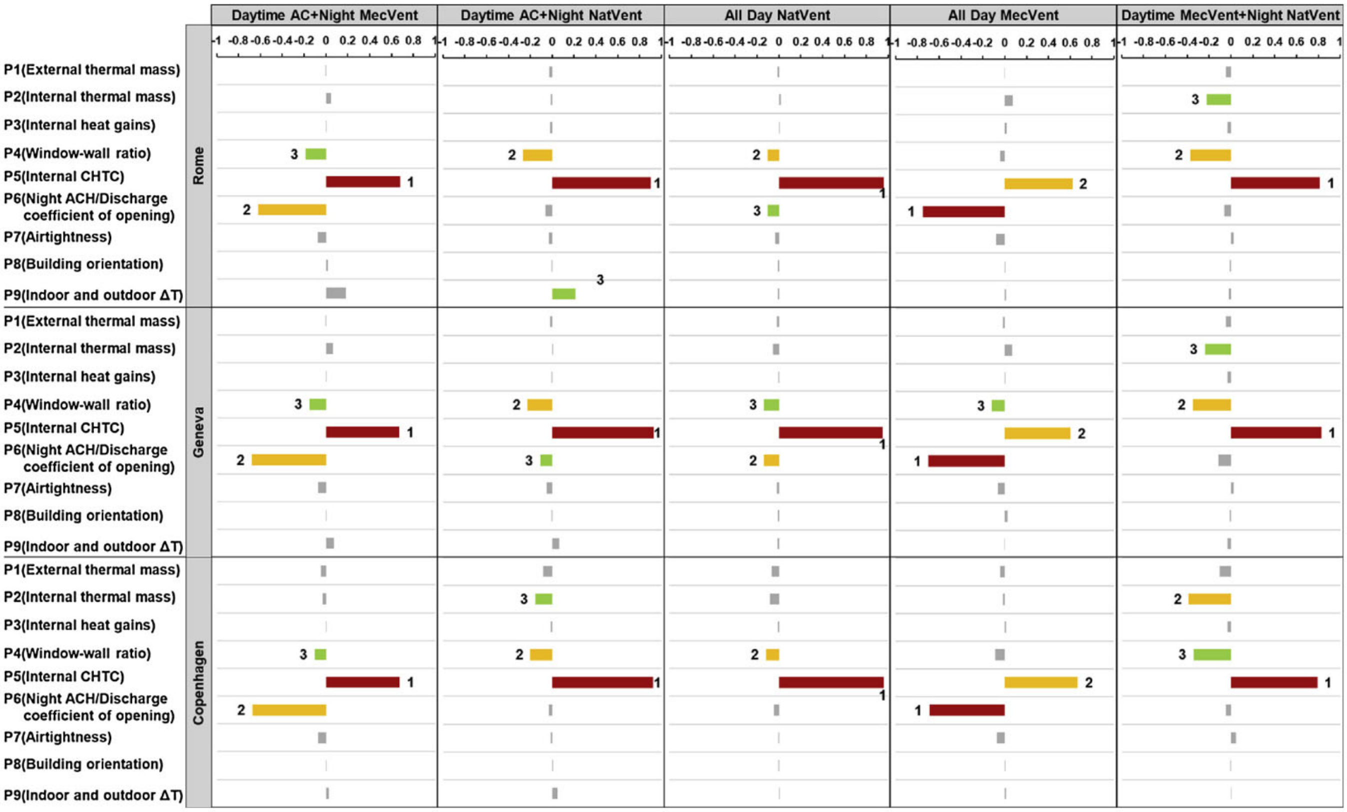

Fig. 3. Sensitivity analysis for TE.

3. Results

3.1. SA for temperature efficiency (TE)

Fig. 3 illustrates the results of the sensitivity analysis ($R^2 = 0.95$) for TE where the three top (and the absolute value of SRC greater than 0.1) influential parameters are labeled. It can be concluded that the internal CHTC is the most influential parameter for all climates and systems, except for the all-day mechanical ventilation system, but still ranking second. P6 (Night ACH) is important for the systems with night mechanical ventilation, while P6 (Discharge coefficient of opening) is not obvious in cases with night natural ventilation. The risk of this happening for the range of discharge coefficient is relatively small and will not influence the level of night natural ventilation rate. However, it is acceptable because the range has been defined according to the bibliography. Increasing window-wall ratio (WWR) always decreases the value of this indicator considerably, except for the all-day mechanical ventilation system. In the daytime mechanical ventilation with night natural ventilation system, the internal thermal mass becomes more influential. Additionally, the colder the weather is, the larger the influence of the internal thermal mass on TE.

It may confuse people that the higher the night ACH is, the lower the value of TEs. Artmann updated the indicator by multiplying TE with daily climatic cooling potential, ACH, and physical parameters of room and air to evaluate the amount of heat removed by night ventilation, demonstrating that increasing ACH will remove more heat (Artmann et al., 2010). Therefore, the temperature efficiency is not suitable to evaluate the heat removal effectiveness affected by different night ACH, but available to evaluate the performance of night ventilation for different scenarios with the same air flow rate.

3.2. SA for temperature difference ratio (TDR)

Fig. 4 shows that the WWR is the most important design parameter for TDR for all systems in all climates. Similar to the SA for TE, P6 is important for the systems with night mechanical ventilation, while not obvious for the systems with night natural ventilation. In cases with the daytime AC system, the internal CHTC tends to have a large influence with a positive SRC. Moreover, the TDR appears to be sensitive to the building airtightness for the systems with night natural ventilation. Increasing the infiltration rate will raise the value of TDR, as it can lower the maximum indoor air temperature. As expected, the colder the weather is, the more influential the building airtightness. For the all-day natural ventilation system and all-day mechanical ventilation system, the internal thermal mass becomes influential, but the sign of its SRC is negative for the former system while positive for the latter system. The reason is that for the former system, the increase of internal thermal mass raises the maximum indoor air temperature while decreases it for the latter system.

3.3. SA for decrement factor (DF)

Fig. 5 shows the sensitivity analysis for the DF. Generally, the most influential design parameters are the internal thermal mass and WWR, whose rank vary slightly in some cases. The increase of WWR raises the fluctuation of indoor air temperature, while the augment of the internal thermal mass level decreases the fluctuation. P6 is also important for the systems with night mechanical ventilation systems and insignificant in the systems with night natural ventilation. Moreover, the value of SRC ranges from −0.4 to −0.2, indicating that the internal CHTC generally has a big influence on DF. Even though the external thermal mass does not have the same obvious influence with the internal thermal mass, some attention should be paid on it, as the value of its SRC ranges from −0.4 to −0.1.

In general, the lower the value of DF is, the less the indoor air is affected by the local weather, which is beneficial for the climate region with high diurnal temperature range and has a great potential for night ventilation. Although the night ventilation can lower the indoor air

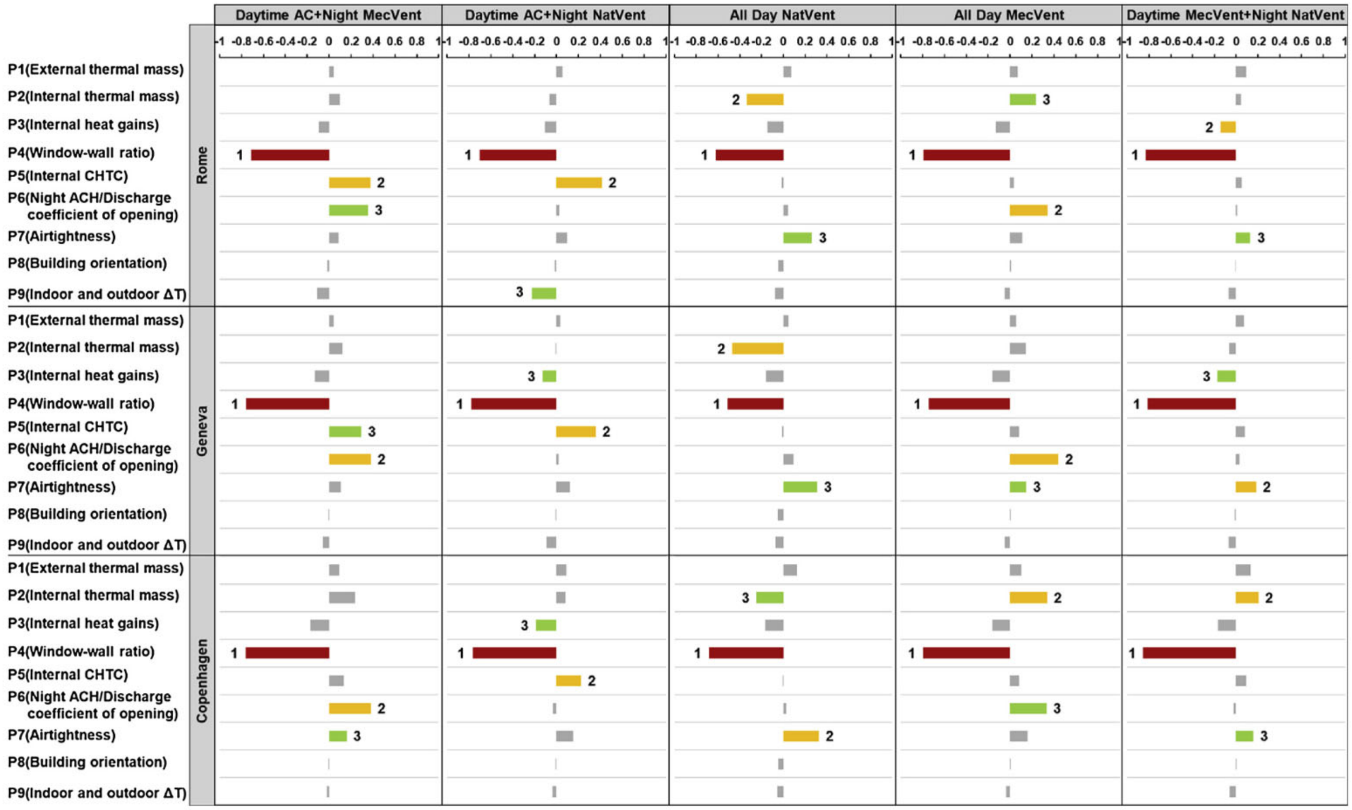

Fig. 4. Sensitivity analysis for TDR.

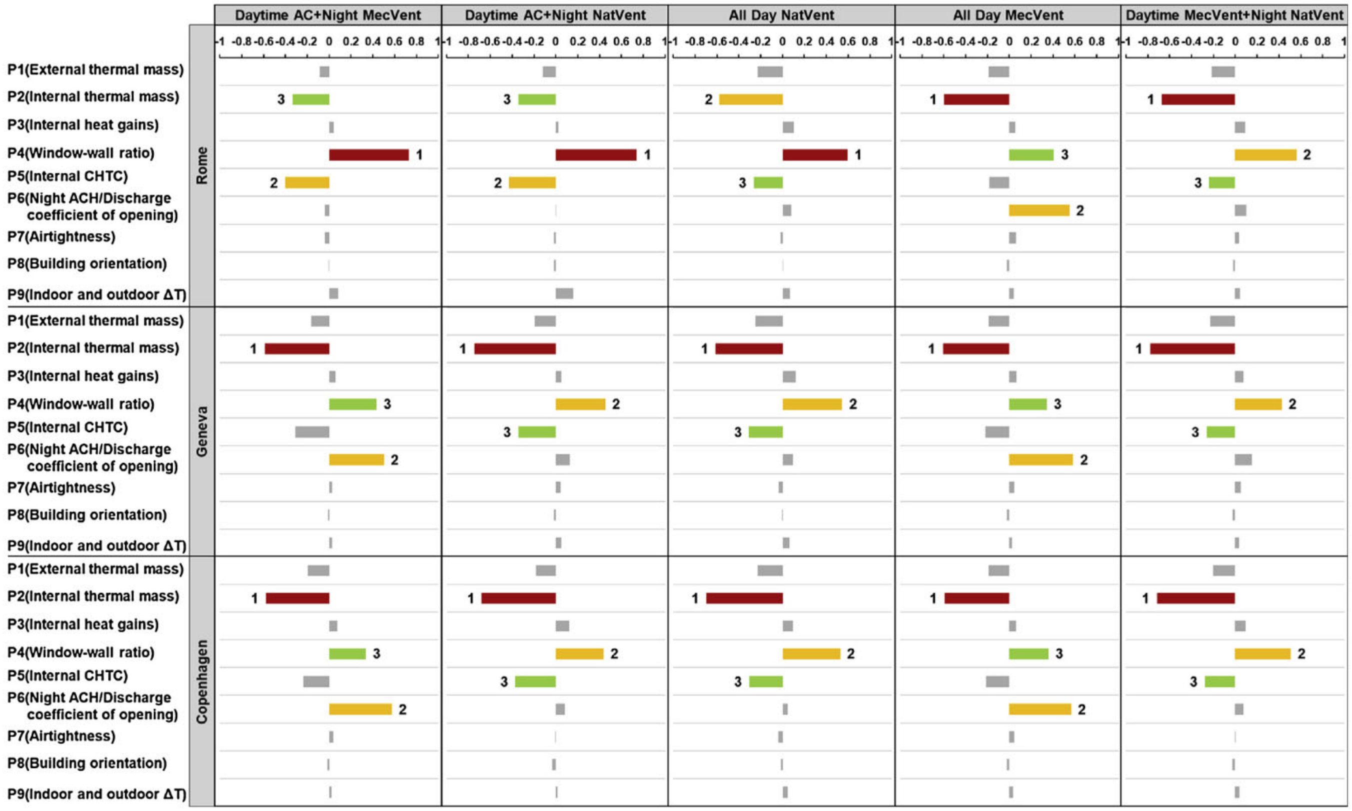

Fig. 5. Sensitivity analysis for DF.

temperature, it also enlarges the indoor air temperature fluctuation which increases the value of DF since the minimum indoor air temperature reduces more.

In such cases, it may be also confusing whether the bigger the value of DF means a better night ventilation performance. Therefore, the DF may be only suitable for the cases with the same building information to compare the scenarios with and without night ventilation or the scenarios with different night airflow rates.

3.4. SA for coefficient of performance (COP) and ventilative cooling advantage (ADV)

Fig. 6 shows the influence of design parameters on COP (Fig. 6(a)) and ADV (Fig. 6(b)). The COP and ADV are only available for the systems with night mechanical ventilation. It can be concluded that the influence of parameters on COP is almost the same for the two systems. The night ACH is the most important design parameter with a negative SRC, followed by the WWR and internal thermal mass whose signs of SRC are both positive. The reason why the night ACH has a negative SRC on COP is that increasing the air flow rate result in more fan electric consumption, while the amount of cooling energy supplied by the fan does not increase linearly with the fan electric consumption. When increasing the WWR and internal thermal mass level, there will be more excess heat stored during the daytime to be removed by the same night ventilation consumption. Attention should be paid on the building airtightness, as its SRC value is about -0.2, indicating that this parameter has some influence on COP.

The influence of design parameters on ADV varies a lot for different systems and locations. The WWR is important for both systems. However, it has a positive SRC on ADV for daytime AC with night mechanical ventilation system while has a negative SRC for the all-day mechanical ventilation system. Undoubtedly, increasing the WWR will increase the cooling system electrical energy consumption of both the scenarios without and with night ventilative cooling which are $Q_{el,c}^{ref}$ and $Q_{el,c}^{scen}$ respectively. The reason why the WWR has a different effect on ADV for two systems may be that increasing WWR will increase $Q_{el,c}^{ref}$ more for the former system while increase $Q_{el,c}^{scen}$ more for the latter system. Night ACH plays an important role in the former system, especially in the medium and cold climate regions, but it is not influential for the latter system. Internal thermal mass ranks second among all design parameters for the former system but is not important for the latter system. It should be noticed that the P2 has a negative SRC on ADV for the former system in Rome, while has a positive SRC for the former system in Geneva and Copenhagen. This indicates that in hot climates, the internal thermal mass level should not be increased without limit, because the night cooling with relatively high-temperature ambient air may not be able to remove all the stored excess heat in the thermal mass during the daytime. Additionally, internal CHTC and internal heat gains have a limited effect on ADV for both systems.

3.5. SA for cooling requirements reduction (CRR)

CRR is not available for the all-day natural ventilation system, because this system does not have daytime mechanical cooling method. Fig. 7 shows that the design parameters have various effects on CRR for different systems and locations. WWR is the most influential parameter in the systems with daytime mechanical ventilation, but not the same influential in the cases with daytime AC. The colder the weather is, the more influential the WWR is for systems with daytime mechanical ventilation. This is probably due to the increasing P4 leads to a different cooling demand increment of the reference scenario without ventilation and the analyzed scenario with ventilation. Generally, the internal thermal mass has a big influence on CRR for the systems with daytime AC, but the influence varies a lot in different locations. It indicates that the internal thermal mass should be arranged properly based on climate conditions and system configurations. Similar to other indicators, the P6 is only significant in the cases with night mechanical ventilation, with a positive SRC. Moreover, the internal CHTC always has a small

Fig. 6. Sensitivity analysis for (a) COP and (b) ADV.

negative SRC on CRR.

3.6. SA for percentage outside the range (POR)

Two comfort models from EN 15251 Category II (EN 15251, 2007) and ASHRAE 55 (ASHRAE 55-2004, 2004) were applied to calculate POR EN 15251 adaptive model category II refers to whether the operative temperature falls into the 80% acceptability limits, while ASHRAE 55 simple model indicates whether the combination of humidity ratio and the operative temperature is in the ASHRAE 55-2004 summer clothes region. Fig. 8 shows the sensitivity analysis for the POR based on the two comfort models. The PORE and PORA refer to the POR with CEN 15251 Category II and ASHRAE 55 simple model respectively.

For EN 15251 model, the WWR is most influential for the last three systems, while its influence is not as obvious for the first two systems which have daytime AC, especially in the cold climate region. The effect of the internal thermal mass on POR varies a lot for different systems and locations. In general, P2 is more influential in medium or cold climate regions, but whether its SRC for the indicator is positive or negative depends on the systems. On the contrary, the PORE is more sensitive to the internal CHTC in non-cold climate regions, and the POR always declines with increasing the internal CHTC. P6 can only make a great difference in this indicator for the all-day mechanical ventilation system. Additionally, some attention should be paid for the building airtightness in the all-day natural ventilation system, as its SRC value ranges from -0.3 to -0.2.

Generally, the influence of design parameters on the ASHRAE 55 simple model is similar to those in EN 15251 adaptive model in most scenarios. However, the influences of WWR, internal CHTC, and night ACH on PORA are quite different or even reverse between the two comfort models for the systems with daytime AC and mechanical ventilation system in Copenhagen. The WWR does not play the same important role in PORA for the last three systems but is more influential for the first two systems when in comparison with PORE in Copenhagen, shown in Fig. 8(b). This might because the ASHRAE 55 simple model takes the humidity ratio into account, while the EN 15251 adaptive model only considers operative temperature.

3.7. SA for degree-hours criterion (DhC) and weighted discomfort temperature index (DI)

As the influence of design parameters on DI are quite similar to those on DhC, the SA results for DI in Fig. 9 are also represented for DhC. The difference between the SA results of DI and DhC is mainly the magnitude of SRC value for some design parameters in some scenarios. Generally, for the two thermal comfort indicators, the WWR is most influential, followed by the internal CHTC. The influence of internal thermal mass on DhC and DI varies a lot in different systems and locations, indicating that the internal thermal mass should be designed properly. P6 is important for the systems with night mechanical ventilation but not obvious for the systems with night natural ventilation. For all-day natural ventilation system, the building airtightness has some impact on the two indicators with negative SRCs. Besides, as expected, the colder the weather is, the larger the influence of the building airtightness is.

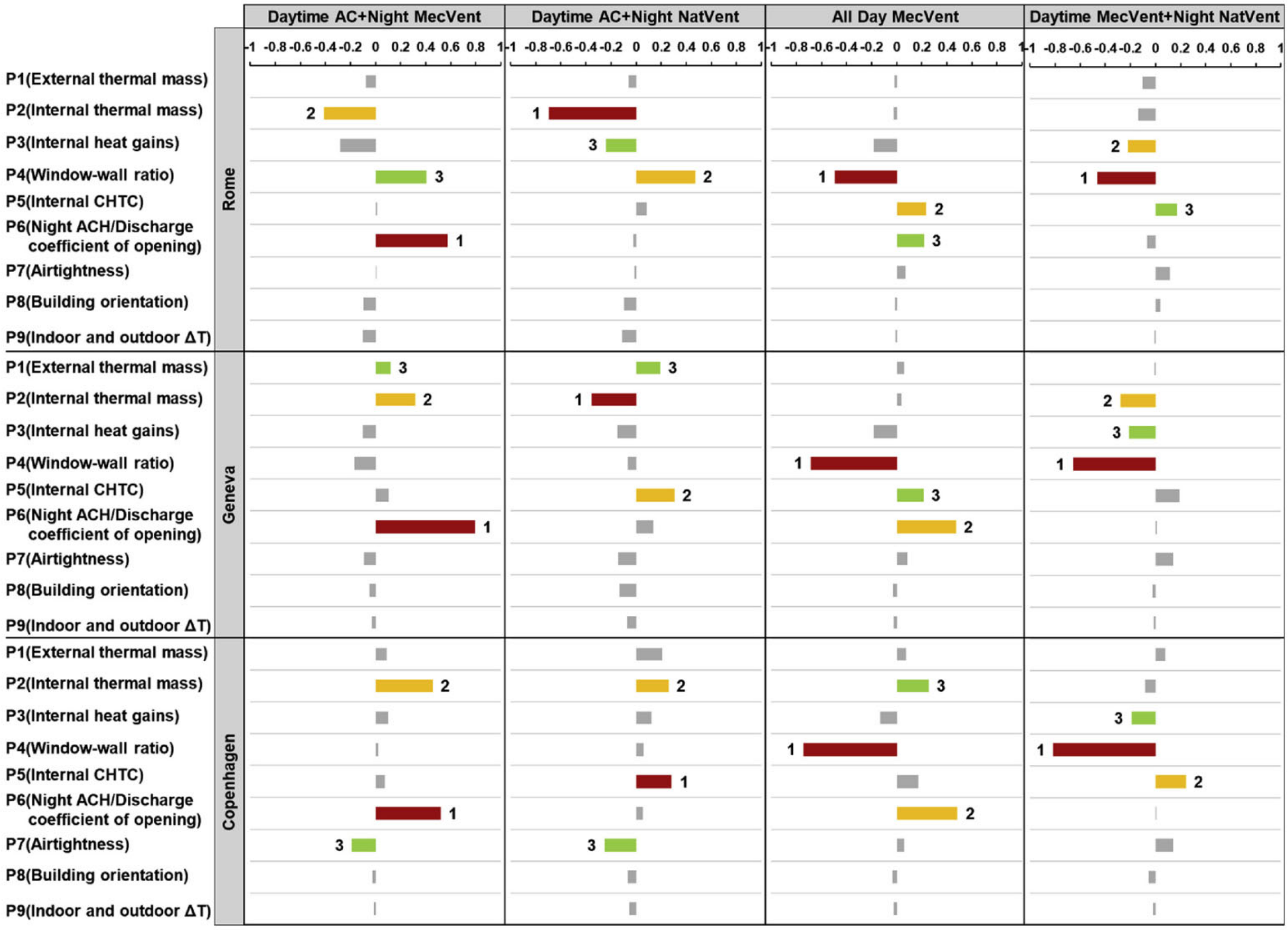

Fig. 7. Sensitivity analysis for CRR.

4. Discussions

4.1. Importance of design parameters

Fig. 10 shows the proportions of the design parameters in the corresponding first, second, third important design parameter for all performance indicators. The 1st important parameter results show that the WWR, internal CHTC, internal thermal mass, and night mechanical ACH are the most important design parameters. The 2nd important parameter results mean that building airtightness and internal heat gains should be taken into consideration when concerning some performance indicators. Apart from the aforementioned six parameters, the results of the 3rd important parameter show that the external thermal mass and threshold temperature ΔT for night ventilation should be paid some attention in certain cases.

In the perspective of the influence of each design parameter on all night cooling performance indicators based on sensitivity analysis results from Section 3, it can be concluded that the WWR always has significant negative SRCs on TE and TDR, but positive SRCs on DF, COP, and the thermal comfort indicators. But there is an exception that WWR has a negative SRC on the PORA for the systems with daytime AC and the all-day mechanical ventilation system in cold climate region. Meanwhile, the signs and values of SRC of WWR on ADV and CRR vary a lot depending on the climates or system configurations. Increasing the WWR will raise the value of ADV and CRR for the systems with daytime AC, while reduces those value for the systems with daytime mechanical ventilation.

The internal CHTC have uniform signs of SRCs for each indicator. Increasing the internal CHTC will decrease the value of thermal comfort indicators to improve thermal comfort, as well as the value of DF to keep the indoor air temperature steadier. On the other hand, increasing the internal CHTC will augment heat removal effectiveness (TE & TDR), energy efficiency (COP & ADV), and cooling energy use reduction (CRR). It means that increasing the CHTC is always beneficial, which can be achieved by selecting appropriate night ventilation mode or optimizing the indoor air distribution to enhance the heat transfer area between the cold air and building elements.

The external thermal mass is much less influential than the internal thermal mass. The former one is only slightly important on the CRR, POR, and DI in some scenarios. The latter one has positive SRCs for COP and negative SRCs on the DF all the time. But the signs of its SRCs for the rest of indicators vary a lot based on the night cooling solutions and climates.

Night ACH always has positive SRCs on TDR, DF, and CRR, but negative SRCs on TE, COP, DhC, DI, PORE, and PORA except for the daytime AC with night mechanical ventilation system in cold climate region. Commonly, increasing the night ACH will reduce the value of ADV. However, the ADV of the all-day mechanical ventilation system in the medium and hot climate regions will benefit from the increase of night ACH.

The building airtightness is only important on the TDR, COP, ADV, CRR, and the thermal comfort improvement indicators in some cases. In general, the colder the weather is, the more influential the building airtightness is. The internal heat gains always have negative SRCs on TDR. Moreover, it will influence the ADV, CRR, and POR for several scenarios a lot. ΔT only has a limited influence on the TE, TDR, and

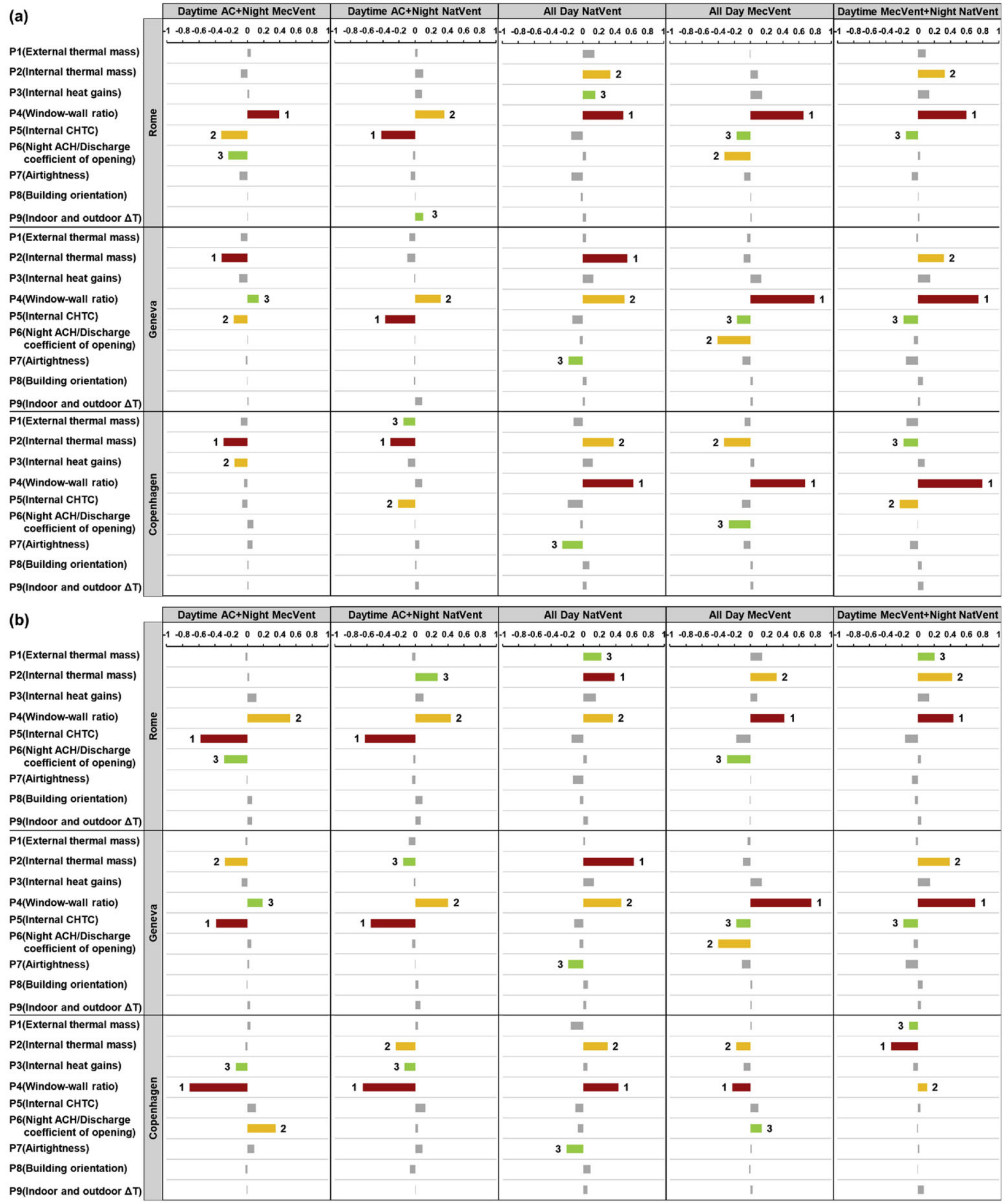

Fig. 8. Sensitivity analysis for (a) POR EN 15251 model and (b) POR ASHRAE 55 model.

thermal comfort improvement indicators for the daytime AC with night natural ventilation system in the hot or medium climate regions. Increasing the ΔT will raise the value of thermal comfort improvement indicators and TE, but reduce the value of TDR.

Building orientation can affect the solar heat gains of the room, and the air flow rate of natural ventilation. However, the influence of building orientation on the night cooling performance is quite low, because the solar heat gains were generally low when compared with the internal heat gains, and the air flow rate does not have a big difference with the orientation changing (shown in Fig. 11). The reason

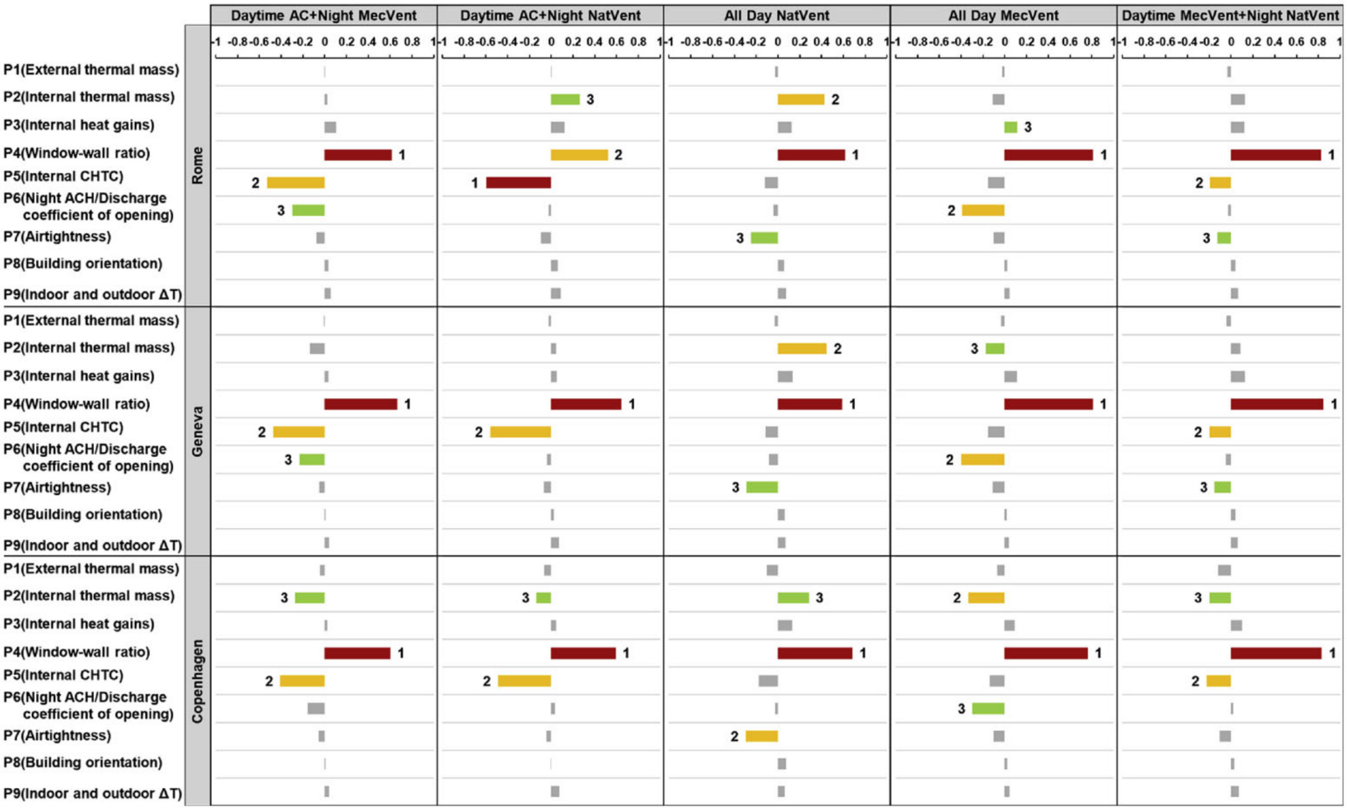

Fig. 9. Sensitivity analysis for DhC and DI.

why the orientation has little influence on the change of air flow rate is that the opening effectiveness in natural ventilation model is calculated automatically in EnergyPlus, which assumes the window can adjust its angle to make the most of wind under different wind directions.

4.2. Night cooling performance

4.2.1. Thermal comfort evaluation

The ability of night cooling to improve thermal comfort performance depends on the night cooling solutions as well as the climate. As the magnitude of DhC and DI for different night cooling solutions varies a lot, the Fig. 12 only shows an overview of the PORE and PORA for the modeled cases. The numbers 1, 2, and 3 represent Rome, Geneva, and Copenhagen, respectively.

The comparison of the mean and median value of POR between different night cooling solutions demonstrates that the all-day natural ventilation system has the highest POR, followed by the daytime mechanical ventilation system with night natural ventilation system, all-day mechanical ventilation system, daytime AC with night natural ventilation system, and daytime AC with night mechanical ventilation system. It also can be concluded that the night mechanical ventilation can provide better thermal comfort with lower POR than night natural ventilation. Both for night natural and mechanical cooling solutions the best performance in the EN 15251 model are obtained with the daytime AC system in Rome, reaching 0%. While in the ASHARE55 model the best performance of night natural and mechanical ventilation are also obtained with the daytime AC system, but in Copenhagen, close to 0% and 5% respectively.

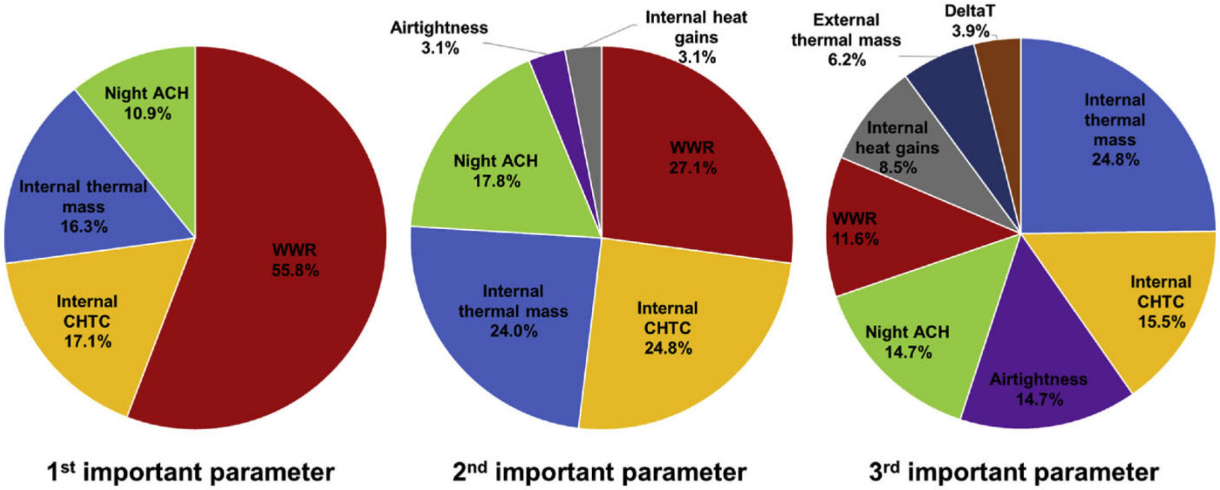

Fig. 10. Pie chart for the top three influential parameters.

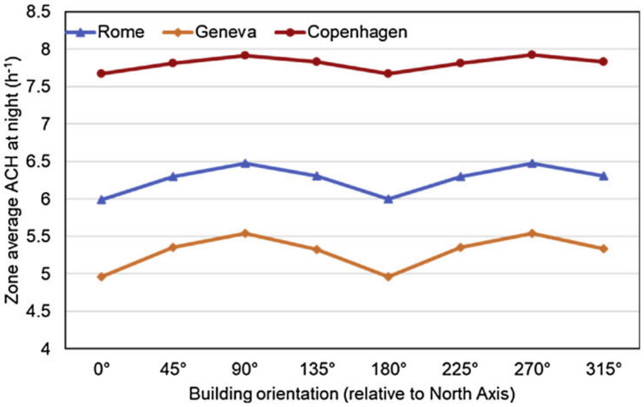

Fig. 11. Zone average ACH at night under different orientations for the daytime AC with night natural ventilation system in three cities.

The value difference between PORE and PORA for the same system in the same climate region shows that the thermal comfort criterion selected will come to different results. The ASHRAE 55 model seems stricter than EN 15251 model, as the PORA is higher than PORE for the same system in the same city. There is a clear trend that the PORE for all systems and PORA for the latter three systems decrease with the location varying from Rome to Copenhagen. This indicates that night ventilation has more application potential in cold climate regions. However, no clear trend exists for the PORA for the first two systems in the same condition. The lowest median and average value of PORA is in Geneva rather than in Copenhagen. One reason may be that the system with daytime AC leaves less excess heat during daytime than other night cooling solutions, leading to the overcooling phenomenon caused by night cooling in cold climate region. Another reason is that the summer comfort range in ASHRAE 55 simple is fixed. Consequently, the zone operative temperature in Rome tending to be higher than the comfort range but lower than the comfort range in Copenhagen.

4.2.2. Energy-saving benefit

The energy efficiency and ability to reduce the cooling energy use of the different night cooling solutions are also very different. Fig. 13 shows the values of COP, ADV, and CRR for different night ventilation solutions. Night mechanical ventilation with daytime AC system tends to have a lower COP but higher ADV than with daytime mechanical ventilation system. This is due to the fact that the daytime AC system can remove more heat and maintain the indoor temperature at the designed level when compared with the daytime mechanical ventilation system. Therefore, less excess heat stored at daytime with AC system will lead to lower COP and higher ADV for night mechanical cooling. ADV can evaluate directly whether the night mechanical cooling is energy saving or not. However, through the comparison of COP with ADV for all-day mechanical ventilation in different climate regions, it can be concluded that high COP does not result in high ADV. COP is not the key indicators to determine whether the night cooling can save energy or not. The result of CRR clearly demonstrates that there is a trend that the value of CRR increases with the climate becoming colder.

For night natural cooling solutions, the best performance for CRR is obtained with the daytime mechanical ventilation system in Copenhagen, reaching 97.1%. For night mechanical cooling solutions, the best performance for ADV and CRR are obtained with the daytime AC system in Copenhagen, reaching 2.4 and 73.8% respectively. While for the COP of night mechanical cooling, the best performance is obtained with daytime mechanical ventilation in Rome, reaching 13.9.

In hot climate region, even though the all-day mechanical ventilation can get a value of COP higher than 10, the night mechanical ventilation does not save energy. Because the ADV is less than 1. However, the CRR of night natural cooling system indicates that this system can be energy-saving, with the highest value of more than 60% for the all-day mechanical ventilation system. While in the cold climate region, all the night ventilation systems can achieve better performance with a higher value of COP, ADV, and CRR, except for the COP of the all-day mechanical ventilation system in Copenhagen. Besides, it is easier to save energy for night mechanical ventilation, with highest and mean value of ADV is 2.4 and 1.1 respectively. For the medium climate region of Geneva, all the values of three indicators are between that in Rome and Copenhagen. The result indicates that the colder the climate, the better performance the night cooling can achieve. However, it should be noticed that the ADV of daytime AC with night mechanical ventilation could be higher than 1 even in Rome, while close to 0 in Copenhagen. Therefore, the night ventilation system should be designed properly based on the climate in order to maximize the energy-saving benefit.

4.3. Applicability of the different performance indicators

The heat removal effectiveness indicators should be used with caution. Firstly, the lack of modeling of the temperature distribution in spaces leads to inaccurate values of the temperature efficiency. Secondly, a comparison of night cooling performance can only be carried out for systems with similar airflow rates by the indicator of TE or with similar building information by the indicator of DF. Under the application conditions, the higher the value of TE or DF, the better the

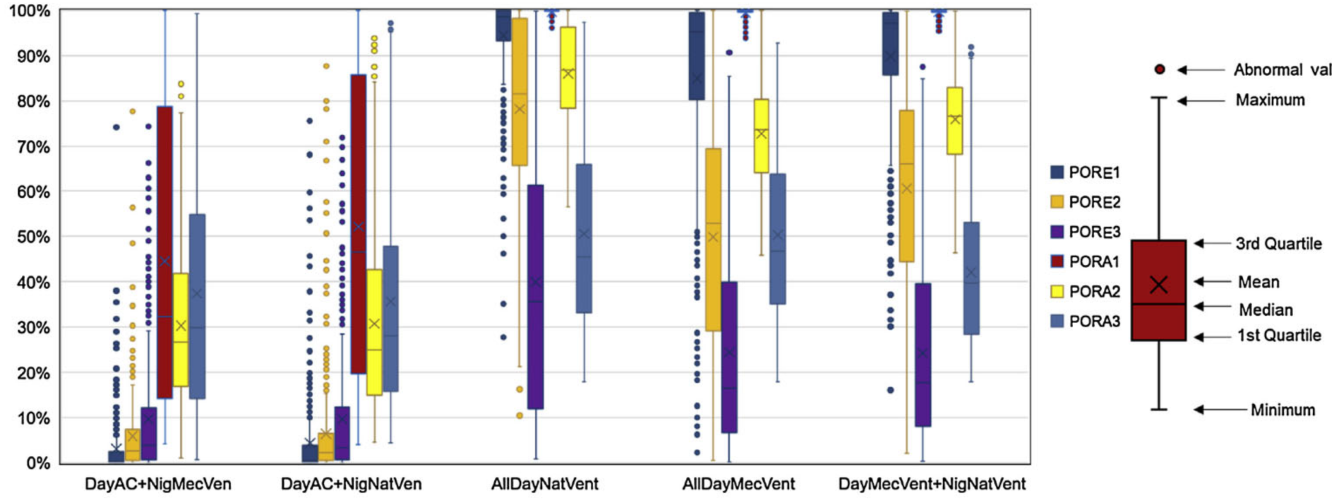

Fig. 12. Box-and-whisker plot of POR for different night cooling solutions.

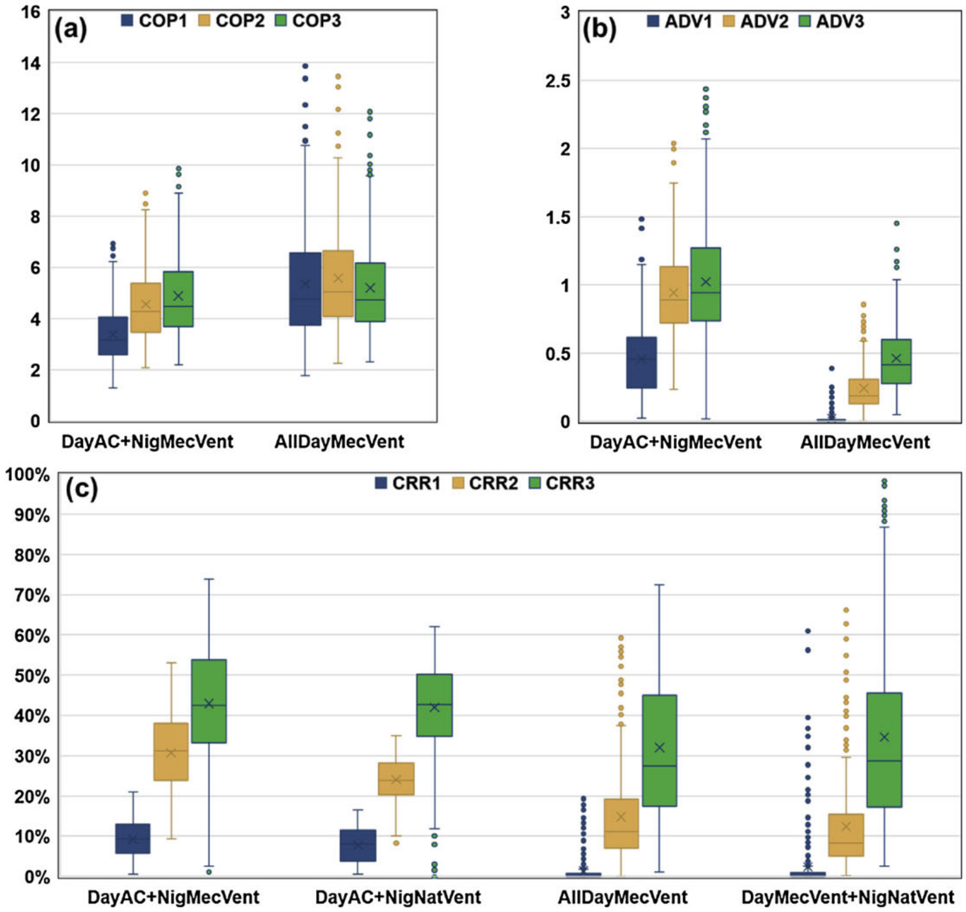

Fig. 13. Box-and-whisker plot of COP (a), ADV (b) and CRR (c) for different night cooling solutions.

performance of night cooling. According to the definition of TDR, the denominator is the ambient temperature swing which is dependent on the local climate condition. Therefore, the TDR is not suitable for the same night cooling system to compare the heat removal effectiveness in different climate regions, but only suitable for the comparison of different system configurations in the same climate region.

The energy-related indicators of COP, ADV, and CRR are used to evaluate energy efficiency and cooling energy use of night cooling. ADV is very useful for night mechanical ventilation systems, while CRR is useful for night natural ventilation systems. Though COP provides a first evaluation of the thermal behavior, the night ventilation energy-saving effect cannot be quantified. Because for the all-day mechanical ventilation system, the high COP does not result in high ADV. Therefore, the COP only evaluates the energy efficiency of ventilation at night time, rather than the energy efficiency for an entire day.

For evaluation of the thermal comfort improvement in the daytime, the best performance indicator is POR because it gives a direct explanation of the percentage outside the comfort range. Furthermore, it can accompany different thermal comfort models or parameters, such as PMV, operative temperature, and dry resultant temperature. Both DhC and DI have some limitations and disadvantages. The biggest limitation is that the thermal comfort threshold value is too simple, such as the operative temperature 26°C or the indoor air temperature 28°C. In addition, the two indicators belong to the cumulative index, of which it may be difficult to evaluate the thermal comfort intuitively.

5. Conclusion

This paper applies a global sensitivity analysis to identify the key design parameters affecting the night ventilation performance. Besides, the applicability and limitations of the performance indicators are evaluated by the results from the parametric simulation. Based on the results of the case study, conclusions can be made as follows.

- The sensitivity analysis shows that the influence of design parameters depends much on the climate conditions and night ventilation system modes. The WWR, internal CHTC, internal thermal mass level, and night mechanical ACH of are the most important design parameters. However, the building airtightness, internal heat gains, external thermal mass level, and threshold temperature ΔT also have limited effect on some indicators in several scenarios. Small differences on the night cooling performance can be noticed for various building orientations and different discharge coefficients of the opening.
- The parametric simulation results show that the way to get the best thermal comfort and energy-saving benefit for night ventilation is equipped with daytime AC. The colder the climate, the better performance the night cooling can achieve. Nevertheless, some measures should be taken to avoid the overcooling effect in cold climate region for the night ventilation with the daytime AC system.
- Some performance indicators have limitations and disadvantages. TE is only suitable to evaluate the performance of different scenarios with similar night ACH, while the DF can be only applied to evaluate the performance of different night ventilation with similar building information. TDR is only available to compare the different night cooling systems in the same climate region. COP is not able to evaluate the energy-saving benefit. DhC and DI are too simple and not able to evaluate the thermal comfort intuitively. Therefore, the ADV, CRR, and POR are recommended to evaluate the night ventilation performance.

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