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Energy performance of mixed-mode office buildings: Assessing typical construction design practices

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A R T I C L E I N F O

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A B S T R A C T

Studies have demonstrated the energy savings potential of mixed-mode ventilated office buildings. Yet, it is important to widen the knowledge about how those buildings have been designed and built in practice, and which design parameters have greater influence on its energy performance. The aim of this paper was to evaluate how building envelope design parameters influence the energy performance of cellular mixed-mode office buildings, in order to identify key design variables. The analysis presents a comparison among literature research studies and typical construction practices from a sample of buildings located in the city of Sao Paulo, Brazil. According to a base case model, established based on the real buildings sample, three sensitivity analysis techniques were performed to obtain relative parameter sensitivity to thermal loads: OFAT, Morris and Monte Carlo. Results showed the importance of the window opening effective area and the reduced impact of the window-to-wall ratio on the energy performance of mixed-mode office buildings. By applying a multivariate regression model, it showed significant in predicting 78.1% of the variance in annual thermal loads. The accurate determination of annual thermal loads into mixed-mode office buildings can be used to optimize the envelope characteristics based on a combination of input data and the building geometry. Findings from this study could also be applied to other locations, provided that similar climatic environment and urban context are taken into account.

1. Introduction

Mixed-mode ventilation (MMV) is an option that allows to combine natural ventilation and mechanical cooling systems as a possible solution to provide cooling, natural ventilation, Indoor Air Quality (IAQ) and thermal comfort to users, while reducing energy use (Brager et al., 2000). This is a relatively new subject; there is no specific guidance on how to simulate or even design such buildings (Salcido et al., 2016), which makes their energy performance analysis a challenging task. Thus, it has attracted attention from researchers, with an increased number of publications on the past two decades (Salcido et al., 2016).

IEA ECBCS Annex 35 (Heiselberg and University A, 2002) and CBE database (Center for the Built Environment (CBE), 2013) were pioneer research studies about the subject, summarizing design principles and performance prediction techniques of MMV buildings. According to Annex 35 report (Heiselberg and University A, 2002), in order to reduce the energy consumption in MMV buildings, designers are required to understand its requirements since the early design stages, which are different from mechanically ventilated buildings. In that sense, the building envelope is a key aspect for the MMV system to work properly. The characteristics of the building envelope, such as glazing surface area, window protection and window type affect the heat gains and losses of the interior spaces, and also help promoting a better use of the natural ventilation system (Hamdaoui et al., 2018). As a result, it provides less use of the air-conditioning system and, therefore, greater energy efficiency (Brager et al., 2000; Mendler et al., 2006).

Latest research studies are specially focused on exploring the following main topics: occupant thermal comfort perception (Damiati et al., 2016; Vecchi et al., 2017; Deuble and de Dear, 2012; Healey, 2014; Luo et al., 2015; Manu et al., 2016; Rijal et al., 2009; Rijal et al., 2012; Rupp and Ghisi, 2017; Rupp et al., 2018; Rowe and Dinh, 2001; De Wilde and Tian, 2010a); building control and model predictive control strategies (Daaboul et al., 2018; Hu and Karava, 2014; Jung et al., 2011; Karava et al., 2012; May-Ostendorp et al.,

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Acronyms

AFN	Airflow Network
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	Building Energy Simulation
CI	Confidence Interval
DOE	Design of Experiments
EE	Elementary Effect
EMS	Energy Management System
ERL	EnergyPlus Runtime Language
MCA	Monte Carlo Analysis
MMV	Mixed-Mode Ventilation
IAQ	Indoor Air Quality
OFAT	One-Factor-At-a-Time
SHGC	Solar Heat Gain Coefficient
SI	Sensitivity Index
SRC	Standardised Regression Coefficient
TMY	Typical Meteorological Year
VSA	Vertical Shadow Angle
WWR	Window to wall ratio

2011; Spindler and Norford, 2009a; Tanner and Henze, 2014; Zhao et al., 2016); modelling techniques and system's thermal and energy performance analysis (Karava et al., 2012; Aradag et al., 2011; Chen et al., 2018; Ji et al., 2009; Lin et al., 2016; Mahdavi and Pröglhöf, 2008; Malkawi et al., 2016; Spindler and Norford, 2009b; Zhai et al., 2011; Wang and Greenberg, 2015). Few works have explored the envelope design optimization of MMV buildings, as it can be seen in the comprehensive literature review conducted by Salcido et al. (2016), which evaluated the potential of MMV systems in office buildings. For instance, the main methodologies adopted in previous studies consisted on either case studies, performed through field monitoring and questionnaires (Deuble and de Dear, 2012; Healey, 2014; Luo et al., 2015; Rowe and Dinh, 2001; Aggerholm, 2003; Blondeau et al., 1997; Brohus et al., 2003; Principi et al., 2003; Wei et al., 2013) and/or modelling, based on simplified representations of reality by using software tools such as EnergyPlus (Wang and Greenberg, 2015; Roetzel et al., 2014; Wang and Chen, 2013; De Wilde and Tian, 2010b; Ben-David and Waring, 2016; Ezzeldin and Rees, 2013; Olsen and Chen, 2003; Pfafferott et al., 2005; Wang et al., 2017), TRNSYS (Blondeau et al., 1997; Engelmann et al., 2014) or computer fluid dynamics (Malkawi et al., 2016; Chang et al., 2004; Gritzki et al., 2003). The areas of uncertainty and future research subjects reported in previous studies include, mainly, the applicability of thermal comfort models (static or adaptive) in MMV buildings (Deuble and de Dear, 2012; Ezzeldin and Rees, 2013), occupant behaviour and occupants' thermal response (Luo et al., 2015; Wang and Chen, 2013), optimal control strategies and control algorithms (Hu and Karava, 2014; Ezzeldin and Rees, 2013), the lack of specific standards or guidelines (Deuble and de Dear, 2012; Emmerich, 2006) and the lack of field studies and/or façade design strategies in accordance to local climates (Deuble and de Dear, 2012; Wang and Greenberg, 2015; Roetzel et al., 2014), which is the focus of the present study.

Santesso and Chvatal (Santesso et al., 2018a) argue that an adequate combination of design parameters could assist the design process of MMV office buildings and result in lower energy consumption. Therefore, the use of sensitivity analysis methods is a valuable path to better understand and explore those characteristics. Since the MMV system relies on natural ventilation to reduce the building's energy consumption, the thermal and energy performance prediction of such buildings through simulation tools is sensitive to many architectural design parameters, what reinforces the importance of exploring optimized combinations of envelope design solutions.

A Systematic Mapping Review was performed to map the frequency of publication on the research topics "sensitivity analysis" and "office buildings". The analysis of the resulting sample (44 journal papers and 18 conference papers) showed a concentration of studies on European climates (45% of the publications), followed by China (19%) and USA (16%). The most used simulation tool was EnergyPlus (56% of the cases) followed by DOE-2 (10%), DesignBuilder and TRNSYS (6% each). Results also demonstrated the small representativeness of MMV office buildings, present in only 5% of the publications, over artificially heated and/or cooled buildings (85% of the cases). Table 1 presents a detailed description of the sensitivity analysis research studies performed in MMV office buildings, from the sample.

Findings from this review reinforce that less attention has been given, in the past, to the study of the energy savings potential of MMV buildings due to building design factors (Salcido et al., 2016). In that sense, Salcido et al. (2016) recommend to extend data collection and publication of case studies of MMV office buildings, in order to help improving its design and the development of specific performance standards, and to focus future research studies on improving energy savings potential by optimizing the building envelope design, in order to maximise the use of natural ventilation and to minimize the use of mechanical cooling energy. It is, therefore, important to widen the knowledge about how those buildings have been designed and built in practice, and which design parameters have greater influence on its energy performance.

Giving the evidence, in current literature, of the research gap on building envelope optimization of MMV office buildings (Salcido et al., 2016; Deuble and de Dear, 2012; Wang and Greenberg, 2015; Roetzel et al., 2014; Santesso et al., 2018a), the aim of this paper is to evaluate how building envelope design parameters influence the energy performance of this type of building and to identify the key design variables. Also, a critical analysis comparing literature research studies on the subject and typical construction practices, focused on real buildings solutions, is discussed.

2. Method

Fig. 1 depicts the steps for the proposed method of the sensitivity analysis process, which integrates the analysis of typical construction design practices with Building Energy Simulations (BES), as explained in the following subsections.

2.1. Step 1: sampled input

Our first objective was to create a sample of MMV office buildings, in order to compare geometry, envelope thermal properties and natural ventilation solutions from real buildings with solutions adopted by technical studies from the literature. First, we selected 153 over a total of 2780 office buildings, from a commercial database of the city of Sao Paulo, Brazil (Buildings. Pesquisa imobi, 2016), based on the following criteria: cellular office buildings operating through a concurrent mixed-mode ventilation system, built over a twenty-year period (between 1995 and 2016) (Neves et al., 2017). Then, we selected 30 scientific publications with research topics related to thermal and energy performance analysis of mixed-mode office buildings (Deuble and de Dear, 2012; Healey, 2014; Luo et al., 2015; Rowe and Dinh, 2001; Hu and Karava, 2014; May-Ostendorp et al., 2011; Malkawi et al., 2016; Wang and Greenberg, 2015; Roetzel et al., 2014; Wang and Chen, 2013; De

Table 1
Research studies about sensitivity analysis in MMV office buildings, focused on architectural design aspects.

Reference	Research objective	Location	Sensitivity analysis method	Output variables	Significant findings
Ballarini and Corrado, 2012 (Ballarini and Corrado, 2012)	Obtain detailed knowledge on the thermal characteristics of an office building for summer performance, focusing on thermal insulation level.	Rome, Italy	Local sensitivity analysis (one-factor-at-a-time)	Heat flow rate (W/m^2)	Weak influence of the envelope on the energy performance of the office building, due to the prevalent influence of the internal heat sources.
Wilde and Tian, 2010 (De Wilde and Tian, 2010b)	Study the impact of climate change on the thermal performance of a theoretical office building.	Birmingham, United Kingdom	Rank regression and multivariate adaptive regression splines (MARS)	Indoor temperature, overheating risk (%), and relative work performance (%)	Lighting, equipment and weather are responsible for more than 90% of the observed variations in most cases. The other factors (like U-values of wall, floor, and roof, infiltration rate) have small effects.
Pollock et al., 2009 (Pollock et al., 2009)	Evaluate envelope thermal characteristics and low carbon at the early design stage, in order to assist the delivery of a sustainable green office building with a high energy performance rating.	Glasgow, Scotland	Local sensitivity analysis (one-factor-at-a-time)	Daylight factor, energy consumption (MWh) and overheating (% of occupied hours over 25/28 °C)	The three top scoring scenarios include solutions where a mixed mode system was incorporated. The scenario with WWR of 32.1% and exposed thermal mass gave the best overall performance.

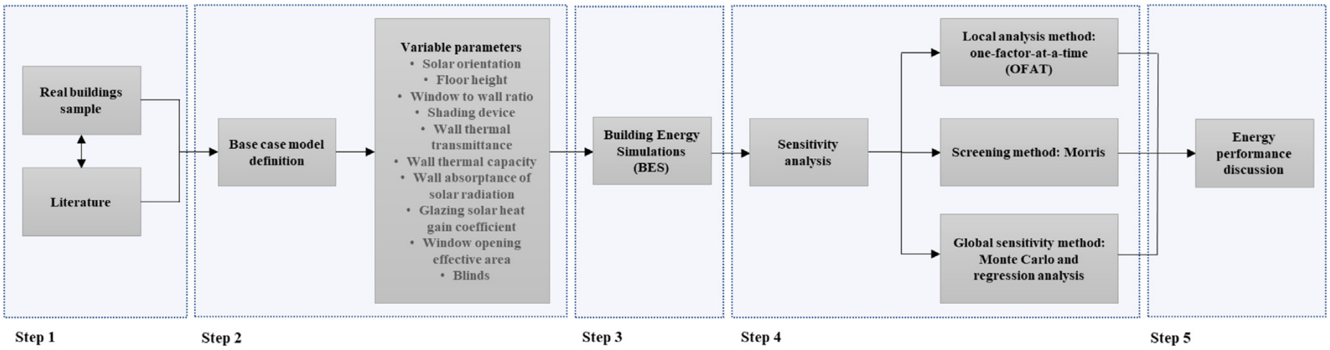

Fig. 1. Energy performance analysis workflow.

Wilde and Tian, 2010b; Aggerholm, 2003; Artmann et al., 2008; Bajenaru et al., 2016; Ben-David and Waring, 2016; Blondeau et al., 1997; Brohus et al., 2003; Chang et al., 2004; Corgnati and Kindinis, 2007; Emmerich, 2006; Engelmann et al., 2014; Ezzeldin and Rees, 2013; Gritzki et al., 2003; Olsen and Chen, 2003; Principi et al., 2003; Pfafferott et al., 2005; Rupp and Ghisi, 2013; Wang et al., 2017; Wei et al., 2013; Zhou et al., 2011), from peer reviewed literature search engines, published within the same period from the buildings sample. Envelope design parameters used either in the real buildings sample and/or the referenced literature were then compared, enabling the selection of architectural design variables that could affect the energy performance of MMV office buildings. The selected variables included building orientation, office floor area, building height, window-to-wall ratio, exterior shading devices, glazing and walls specifications, natural ventilation strategy and window type. The results showing a comparison between typical construction practices versus theoretical studies are presented in tables and histograms, reporting frequency and cumulative percentage.

2.2. Step 2: base case model definition

Data obtained from the real buildings sample and literature provided a robust support to the development of the energy performance analysis of such buildings, given the context of practical restrictions resultant from the building industry and allowing the development of an analysis focused in the Design of Experiments (DOE), i. e., valid and defensible solutions. Therefore, results from the previous analysis were used to define a base case model, adopted as a reference to the present study. A thermal zone was defined to represent a cellular office room located at an intermediate level within a multi-floor office building (Fig. 2). The floor and ceiling were considered to be both adiabatic and no energy transfers occur through them. The geometry and envelope parameters were chosen according to the mean values of continuous variables (office room area, WWR, window opening effective area) and to the highest frequency values of categorical variables (number of floors, solar orientation, room shape, natural ventilation strategy, shading devices) found in the real buildings sample. Table 2 summarizes the base case model characteristics and statistical parameters that reinforces the representativity of the selection.

2.3. Step 3: Building Energy Simulations (BES)

Building Energy Simulations (BES) were carried out using EnergyPlus version 8.7 (EERE. EnergyPlus Engineering Reference, 2014), an energy simulation engine validated by ASHRAE Standard 140 (ASHRAE, 2014). The weather file used to perform the simulations is a Typical Meteorological Year (TMY), based on weather data from the years 2000–2010, available in an EnergyPlus weather file (epw) format for the city of Sao Paulo, Brazil (LABEEE, 2016).

Walls were modelled with three layers, being both inner and outer layers responsible to vary the thermal transmittance and the mid-layer responsible to vary the thermal capacity. Parameters related to windows (window to wall ratio, exterior shading devices,

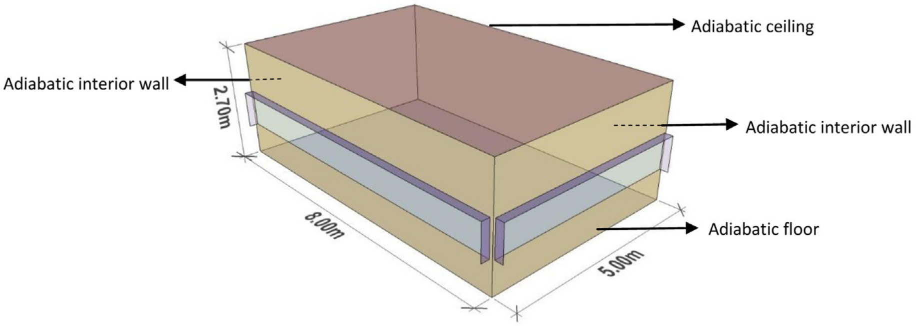

Fig. 2. Representation of the base case model.

Table 2
Base case model characteristics.

Parameter	Unit	Value	Reference
Room's solar orientation (azimuth angle of the long axis)	°	SE (225)	Frequency = 34% (sample analysis)
Office room area	m^2	40 (5 m × 8 m)	CI 95% = 37.1, 45.61 (sample analysis)
Floor number	m	6th floor (intermediate level of a 12-floor building)	Frequency = 32% (sample analysis)
Ceiling height	m	2.7	CI 95% = 2.65, 2.70 (sample analysis)
Window-to-wall ratio	%	30	CI 95% = 27.55, 33.65 (sample analysis)
Exterior shading device (vertical shadow angle)	°	0 (no shading devices)	Frequency = 76% (sample analysis)
Blinds	–	0 (no blinds)	–
Glazing thermal transmittance	$W/(m^2.K)$	5.67 (single pane)	Frequency = 100% (sample analysis)
Glazing solar heat gain coefficient	–	0.90 (clear glass)	Frequency = 74% (sample analysis)
Slab thermal capacity	$kJ/(m^2.K)$	295 (10 cm concrete slab)	–
Wall thermal transmittance	$W/(m^2.K)$	2.75 (mortar 2 cm + concrete block 14 cm + mortar 2 cm)	–
Wall thermal capacity	$kJ/(m^2.K)$	238 (mortar 2 cm + concrete block 14 cm + mortar 2 cm)	–
Wall absorptance of solar radiation	–	0.5 (medium colour)	Frequency = 48% (sample analysis)
Natural ventilation strategy	–	Cross ventilation (adjacent facades)	Frequency = 66% (sample analysis)
Window opening effective area	%	27 (Top hung (Von Grabe et al., 2014))	Frequency = 84% (sample analysis)
Internal loads – occupancy	$Persons/100m^2$	14	Brazilian air-conditioning standard (ABNT, 2008)
Internal loads – lights	W/m^2	9.7	Level A from the Brazilian building energy efficiency labelling system for commercial buildings (Brasil. Portaria nº 53 and d, 2009)
Internal loads – equipment	W/m^2	10.7	Brazilian air-conditioning standard (ABNT, 2008)
Occupancy schedule	h	Weekdays from 8 a.m. to 6 p.m. No occupancy or internal loads on weekends	–

Vertical shadow angle = the angle between the base of the window and the edge of the horizontal shading device (0° = no shading device; 45° = shading device of the same size as the window height)
CI = Confidence Interval

window opening effective area, blinds) varied uniformly between both external facades.

The cooling system was modelled using an ideal air conditioning system. Outdoor airflow rate was modelled according to the Brazilian Health Surveillance Agency (ANVISA, 2003), meaning 27 m^3/h.person (0.0075 m^3/s.person). Assumed setpoints were 25 °C for cooling and 20 °C for heating. Natural ventilation was modelled with the multizone Airflow Network (AFN) model (Von Grabe et al., 2014). One limitation of the AFN model is its inability to control the window opening area, since there is no built-in option for that. An EnergyPlus runtime language (ERL) code was written through Energy Management System (EMS) to override the window control modulation, in order to have a binary control (opened/closed). Blinds were set to block beam solar radiation and it operates independently from the natural ventilation system.

For the wind pressure coefficients, we employed the surface average calculation built-in option for high-rise buildings (ASHRAE, 2005), which is valid only for rectangular buildings. The discharge coefficient (Cd) was set as 0.6, which corresponds to the discharge coefficient of a standard circular sharp-edged orifice (Jones et al., 2016; ASHRAE, 2005; Allard and Utsumi, 1992; Flourentzou et al., 1998). Nevertheless, since its value vary by window type, it is adjusted according the window opening effective area, which is a variable parameter.

Since current international comfort standards still did not establish a specific thermal comfort model for MMV buildings, the adaptive model was found to be applicable to control the environmental conditions, especially when using natural ventilation (Deuble and de Dear, 2012; Luo et al., 2015; Rupp and Ghisi, 2017). Hence, a meta-programming of the adaptive model behaviour (ASHRAE, 2017) was implemented through the EMS functionality in EnergyPlus, as follows:

- The cooling system turns on and windows are closed if the following two conditions are met simultaneously: the zone is occupied (weekdays from 8 a.m. to 6 p.m.) and the zone sensor called ‘thermal comfort ASHRAE 55 adaptive model 80% acceptability status’ is set as 0, which means that the operative temperature is outside the comfort limits (EERE, 2014).

- The cooling system turns off and windows are opened if the following three conditions are met simultaneously: the zone is occupied; the zone sensor called ‘thermal comfort ASHRAE 55 adaptive model 80% acceptability status’ is set as 1, which means that the operative temperature is within the comfort limits (EERE, 2014); and the outdoor temperature is below the zone operative temperature.
- The cooling system turns off and windows are closed if the zone is unoccupied.

The annual output cooling energy demand (kW) was selected as the dependent variable. Therefore, ten independent (predictor) variables and one dependent (response) variable were defined.

It is also important to mention some EnergyPlus modelling limitations, especially when coupling natural ventilation (AFN) and heat transfer models. The airflow calculation through the window opening is not affected by the presence of an interior or exterior shading device on the window. At the same time, the window opening status does not affect the heat transfer calculation, which is always performed as if the windows were closed (EERE, 2014). The impacts of those issues are included in the discussion section.

2.4. Step 4: sensitivity analysis

Ten variable parameters (predictors) were chosen to perform the sensitivity analysis, based on their influence over the annual energy demand (kW) of MMV office buildings. They are: solar orientation, floor height, window-to-wall ratio, exterior shading device, wall thermal transmittance, wall thermal capacity, wall absorptance of solar radiation, glazing solar heat gain coefficient, window opening effective area, and blinds (Table 3). For each independent variable, specific values (for discrete variables) or ranges (for continuous variables) were considered, in order to represent all feasible possibilities, present in MMV office buildings, considering practical achievability and typical construction practices in the city of Sao Paulo, Brazil, obtained from the real buildings sample.

Sensitivity analysis is an important tool in building energy assessment to determine energy saving measures and explore key factors influencing energy use of buildings. There are many different methods of sensitivity analysis, however, sometimes, they do not yield equivalent results. Therefore, due to the importance of knowledge of sensitive buildings input parameters in order to provide more reliable energy saving and to determine and investigate the influence of each variable parameter to the total energy performance of MMV office buildings, three sensitivity analysis methods were compared: Local Sensitivity Method, Screening Method, and Global Sensitivity Method, as follows. Based on results, it was observed which parameters are most highly correlated with the outputs.

2.4.1. Local sensitivity method: one-factor-at-a-time (OFAT)

The OFAT sensitivity analysis method evaluates the energy performance variation of each factor separately, while all the others are kept constant within a base case model. The main disadvantages of this method are that it only allows to explore a small portion of the possible combinations of input values (Tian, 2013), since the correlation between design parameters is not considered (Heiselberg et al., 2009; Delgarm et al., 2018); and it could give misleading results for nonlinear models (Morris, 1991). Nevertheless, many researchers have been using this method due to its low computational cost, easy implementation and interpretation of results (EERE, 2014; Delgarm et al., 2018).

Continuous variables were discretized, according to the previously set sensitivity analysis ranges and considering continuous sampling periods, resulting in a total of 80 simulation models, as shown in Table 4.

Results were compared to the base case model to evaluate which design parameters were most sensitive to energy performance. The Sensitivity Index (SI) was used to calculate each design parameter sensitivity, through Equation (1) (Heiselberg et al., 2009). The sensitivity index informs how sensitive the input data are for the output data, since it calculates, for each input data, the difference between the output and the base solution. According to its results, it is possible to understand the relationship between input and output variables and to detect the most influential parameters as a high SI value means high order interactions.

$$SI = \frac{E_{max} - E_{min}}{E_{max}} 100\% \tag{1}$$

where E_{max} and E_{min} represent the maximum and minimum values for annual output cooling energy demand (kW), respectively.

2.4.2. Screening method: morris

The Morris method was created to help dealing with computational models that have a moderate-to-large number of inputs, allowing to visualize which inputs have an important effect on a

Table 3
Variable parameters and assumed values/ranges.

Parameter	Symbol	Distribution	Unit	Sensitivity analysis ranges
Room's solar orientation (azimuth angle of the long axis)	–	Discrete	°	NW (45), NE (135), SE (225), SW (315)
Floor height (in relation to the ground level)	–	Discrete	m	2.7, 5.4, 8.1, 10.8, 13.5, 16.2, 18.9, 21.6, 24.3, 27, 29.7, 32.4
Window to wall ratio	WWR	Continuous	%	Minimum = 10 Maximum = 70
Exterior shading device (vertical shadow angle)	VSA	Continuous	°	Minimum = 0 (no shading devices) Maximum = 45 (equal to window height)
Wall thermal transmittance	Uwall	Continuous	$W/(m^2.K)$	Minimum = 0.3 Maximum = 3.7
Wall thermal capacity	TCwall	Continuous	$kJ/(m^2.K)$	Minimum = 10 Maximum = 360
Exterior wall absorptance of solar radiation	αwall	Continuous	–	Minimum = 0.2 (white) Maximum = 0.9 (black)
Glazing solar heat gain coefficient	SHGC	Continuous	–	Minimum = 0.2 (high performance glass) Maximum = 0.87 (clear glass)
Window opening effective area	A_{eff}	Continuous	%	Minimum = 5 (top hung window with stopper (CIBSE, 2005)) Maximum = 90 (turn window (CIBSE, 2005))
Blinds	–	Discrete	–	0 (No), 1 (Yes)

Table 4
Assumed values for the OFAT analysis.

Parameter	Unit	Values
Solar orientation (azimuth angle of the long axis)	°	NW (45), NE (135), SE (225), SW (315)
Floor height	m	2.7, 5.4, 8.1, 10.8, 13.5, 16.2, 18.9, 21.6, 24.3, 27, 29.7, 32.4
Window to wall ratio	%	10, 20, 30, 40, 50, 60, 70
Exterior shading device (vertical shadow angle)	°	0, 5, 10, 15, 20, 25, 30, 35, 40, 45
Wall thermal transmittance	W/(m^2.K)	0.30, 0.73, 1.15, 1.58, 2.00, 2.43, 2.85, 3.28, 3.70
Wall thermal capacity	kJ/(m^2.K)	10, 45, 80, 115, 150, 185, 220, 255, 290, 325, 360
Wall absorptance of solar radiation	–	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
Glazing solar heat gain coefficient	–	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
Window opening effective area	%	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
Blinds	–	0, 1

certain output (Morris, 1991). It is also based on random OFAT designs, but the baseline changes in every step (EERE, 2014). One of the main advantages of using this method is that the number of simulations is reduced when compared to the global method (EERE, 2014; Heiselberg et al., 2009). Compared to the local method, its main advantage is that it indicates if the parameter variation is non-linear or mutually correlated (Heiselberg et al., 2009).

Simlab (SIMLAB. v2.2, 2011) was used to generate the input vectors through the factorial sampling method proposed by Morris (1991) and EnergyPlus was used to run the simulations. After establishing two extreme values for each design parameter (Table 2), a normal probability density function was assigned to each continuous variable. In order to enable the analysis, two discrete variables (solar orientation and blinds) were excluded. The discrete number of values (p-levels) for each design parameter was set as four (p = 4). To create the sampled points, randomly selected on a p-values regular grid, the procedure was repeated four times (r = 4), which is a recommended number in the literature (Heiselberg et al., 2009), to assure that the region of variation is reasonably covered for all design parameters. Therefore, the number of simulations to calculate the output values was 36, as shown in Table 5.

After running all simulations, the method of Elementary Effects (Morris, 1991) was applied to assess the influence of each design parameter over the output. For a given variable parameter (x), the Elementary Effect (EE) of the ith input is defined as (Eq. (2)):

$$EE = d_i(x) = \frac{y[x_1,\ x_2,\ \ldots, x_{i-1}, x_i + \Delta, x_{i+1},\ \ldots, x_k) - y(x)}{\Delta} \tag{2}$$

The mean and standard deviation of the elementary effects were calculated according to Equations (3) and (4) (Heiselberg et al., 2009) and plotted in a two-dimensional graph. The mean value (μ) determines the importance of each design parameter and the standard deviation (σ) measures the interactions with other factors and possible non-linear effects. Therefore, low values of both indicate a non-influential input, while high values indicate the key variables (Tian, 2013).

$$\mu = \sum_{i=1}^{r} |EE_i|/r \tag{3}$$

$$\sigma = \sqrt{\sum_{i=1}^{r} |EE_i - \mu|^2/r} \tag{4}$$

2.4.3. Global sensitivity method: Monte Carlo and regression analysis

Global sensitivity methods are able to analyse the influences of uncertain inputs over the whole input space, which means that the output variability of all design parameters is evaluated simultaneously (Tian, 2013; Heiselberg et al., 2009). The global approach is a more reliable option for building energy analysis (Tian, 2013), since the design parameters are often dependent on the interactions between each other. The disadvantages, however, are the high computational demand, compared to local sensitivity methods (Tian, 2013). Between global methods, we chose the regression analysis to evaluate our sample. This is the most widely used sensitivity analysis method within the building energy analysis research field, since it is faster to compute and easier to understand (Tian, 2013).

To develop the global sensitivity analysis, a coupling code with EnergyPlus software was created using the Python language. The code was written to modify key parameters' values of several EnergyPlus input data files (.idf extension) and to automate the data processing of a group of simulation models. It is an open source code that can be downloaded in the following link: http://www.iau.usp.br/laboratorios/lca/index.php/trabalhos-conforto (Santesso et al., 2018b).

The base case model was used as a base case file to generate a sample of EnergyPlus input files, covering different combinations of variables. The Monte Carlo Analysis (MCA) was chosen as the random sampling method to select the values for each input parameter, in order to compose a group of different input data files,

Table 5
Assumed values for the Morris analysis.

Parameter	Unit	Values (set through the factorial sampling method)
Floor height	m	4.9, 14.1, 21.0, 30.2
Window to wall ratio	%	15, 33, 47, 65
Exterior shading device (vertical shadow angle)	°	4, 21, 32, 43
Wall thermal transmittance	W/(m^2.K)	0.56, 1.60, 2.40, 3.44
Wall thermal capacity	kJ/(m^2.K)	37, 144, 226, 333
Wall absorptance of solar radiation	–	0.25, 0.47, 0.63, 0.85
Glazing solar heat gain coefficient	–	0.25, 0.47, 0.63, 0.85
Window opening effective area	%	11, 37, 58, 84

where all ten parameters were varied concurrently. Uniform distributions were applied to each variable parameter since the specified range contains equally probable design choices, as shown in Table 6. Statistical estimation of average, variance, standard deviation and coefficient of variation were used to define the number of cases selected for simulation, resulting in a total of 8000 cases, 2000 corresponding to each solar orientation.

Boxplots were used to analyse trends and concentrations, in order to assess the influence and relative importance of each design parameter on the output variable. Multivariate linear regression was performed to analyse relative parameter sensitivity to energy demand. Standardised Regression Coefficients (SRC) were used as indicators, in order to quantify errors and non-linearities among the parameters. They were obtained by normalizing each regression coefficient by the standard deviation of the parameter value (Equation (5)) (Hygh et al., 2012; Morgan and Henrion, 1990).

$$U_{SRC}(x_i,\ y) = \frac{\beta_j\, x\, s_j}{s_y} \tag{5}$$

where y is the predicted annual energy demand (kW/yr), x_i is the design parameter, β_j is the regression coefficient, s_j is the design parameter's standard deviation and s_y is the predicted annual energy demand's standard deviation.

3. Results

3.1. Sampled input results and base case model definition

The first research step consisted in gathering envelope and natural ventilation design solutions of 153 mixed-mode office buildings from the city of Sao Paulo, Brazil, built over a twenty-year period, and compare it with the technical literature, published within the same period, in order to understand how far research has come in addressing this topic. The selected papers (Deuble and de Dear, 2012; Healey, 2014; Luo et al., 2015; Rowe and Dinh, 2001; Hu and Karava, 2014; May-Ostendorp et al., 2011; Malkawi et al., 2016; Wang and Greenberg, 2015; Roetzel et al., 2014; Wang and Chen, 2013; De Wilde and Tian, 2010b; Aggerholm, 2003; Artmann et al., 2008; Bajenaru et al., 2016; Ben-David and Waring, 2016; Blondeau et al., 1997; Brohus et al., 2003; Chang et al., 2004; Corgnati and Kindinis, 2007; Emmerich, 2006; Engelmann et al., 2014; Ezzeldin and Rees, 2013; Gritzki et al., 2003; Olsen and Chen, 2003; Principi et al., 2003; Pfafferott et al., 2005; Rupp and Ghisi, 2013; Wang et al., 2017; Wei et al., 2013; Zhou et al., 2011) analysed thermal comfort, energy efficiency and/or air quality of mixed-mode office buildings located worldwide (Europe, China, USA, Canada, Australia, Brazil, India, Japan, South Korea, Egypt, and Saudi Arabia), through building energy simulation, field monitoring and/or survey. Table 7 presents a summary of the gathered information.

It is important to highlight remarkable differences between both samples. A three-storey building is the most frequent option in technical literature, since it represents, in a computer simulation, heat transfers through the ground floor, the intermediate floor and the top floor. However, the building terrain type/surroundings and the height from the ground affect the wind speed approaching a building (ASHRAE, 2005), which may interfere on the building's natural ventilation performance. Despite cross ventilation at adjacent facades being the most frequent solution found in the real buildings sample, this design strategy was not found in studies from specialized literature. Single-sided ventilation presented the highest occurrence (35%), followed by cross ventilation at opposite facades (30%). Conversely, this last option was not found in the real buildings sample. No studies from the literature informed the value used for wall absorptance of solar radiation, regardless of being an important information to calculate heat gains through the envelope. Most part of the studies from the literature (67%) also did not mention the type of window frame or the window opening effective area, an important variable to calculate natural ventilation performance.

Figs. 3–5 present frequency and cumulative percentage results for geometry, envelope and natural ventilation parameters of the real buildings sample. The variables natural ventilation strategy, window-to-wall ratio and wall absorptance of solar radiation were raised on field, for a reduced sample of 50 buildings. The visited buildings were selected based on average and standard deviation results of the variables floor area, room area and number of floors, from the whole sample (153 buildings). The highest frequency values, presented in Figs. 3–5, were used as input parameters to the base case model, adopted as a reference to the present study.

3.2. Sensitivity analysis results

The results of the simulation-based sensitivity analyses are provided based on three approaches: the OFAT local sensitivity method, the Morris screening method, and the Monte Carlo and regression analysis global sensitivity method. The analyses aimed to find out how input variables affect the energy performance of a typical MMV cellular office building located in the humid

Table 6
Assumed values for the Monte Carlo analysis.

Parameter	Unit	Ranges/Values	Precision
Solar orientation (azimuth angle of the long axis)	°	NW (45), NE (135), SE (225), SW (315)	–
Floor height	m	2.7, 5.4, 8.1, 10.8, 13.5, 16.2, 18.9, 21.6, 24.3, 27, 29.7, 32.4	–
Window to wall ratio	%	Minimum = 10 Maximum = 70	0.01
Exterior shading device (vertical shadow angle)	°	Minimum = 0 (no shading devices) Maximum = 45 (equal to window height)	0.01
Wall thermal transmittance	$W/(m^2.K)$	Minimum = 0.3 Maximum = 3.7	0.01
Wall thermal capacity	$kJ/(m^2.K)$	Minimum = 10 Maximum = 360	0.1
Wall absorptance of solar radiation	–	Minimum = 0.2 (white) Maximum = 0.9 (black)	0.01
Glazing solar heat gain coefficient	–	Minimum = 0.2 (high performance glass) Maximum = 0.9 (clear glass)	0.01
Window opening effective area	%	Minimum = 5 (top hung window with stopper (CIBSE, 2005)) Maximum = 90 (turn window (CIBSE, 2005))	0.01
Blinds	–	0 (No), 1 (Yes)	–

Table 7
Comparison of design solutions between real buildings and technical literature.

Parameter	Real buildings sample	Literature		
	Highest occurrence (frequency)	Highest occurrence (frequency)	Different scenarios of analysis (paper reference)	Not informed (number of papers)
Office floor area	40 m^2 (40%)	20 m^2 (56%)	(Blondeau et al., 1997; Rupp and Ghisi, 2013)	19
Number of floors	12 floors (32%)	3 floors (61%)	–	12
Solar orientation	NW-SE (34%)	N–S (60%)	(Engelmann et al., 2014; Rupp and Ghisi, 2013; Wang et al., 2017)	10
Building shape	Rectangular (89%)	Rectangular (79%)	–	11
Exterior shading devices	No shading devices (76%)	No shading devices (57%)	Roetzel et al. (2014)	7
Window-to-wall ratio	20% (40%)	50% (25%)	(Roetzel et al., 2014; Gritzki et al., 2003; Rupp and Ghisi, 2013)	10
Wall absorptance of solar radiation	Medium colour (48%)	–	–	30
Natural ventilation strategy	Cross ventilation at adjacent facades (66%)	Single-sided ventilation (35%)	–	7
Type of window frame	Top hung – 27% of window opening effective area (84%)	100% of window opening effective area (30%)	(Wang and Greenberg, 2015; Chang et al., 2004; Rupp and Ghisi, 2013)	20

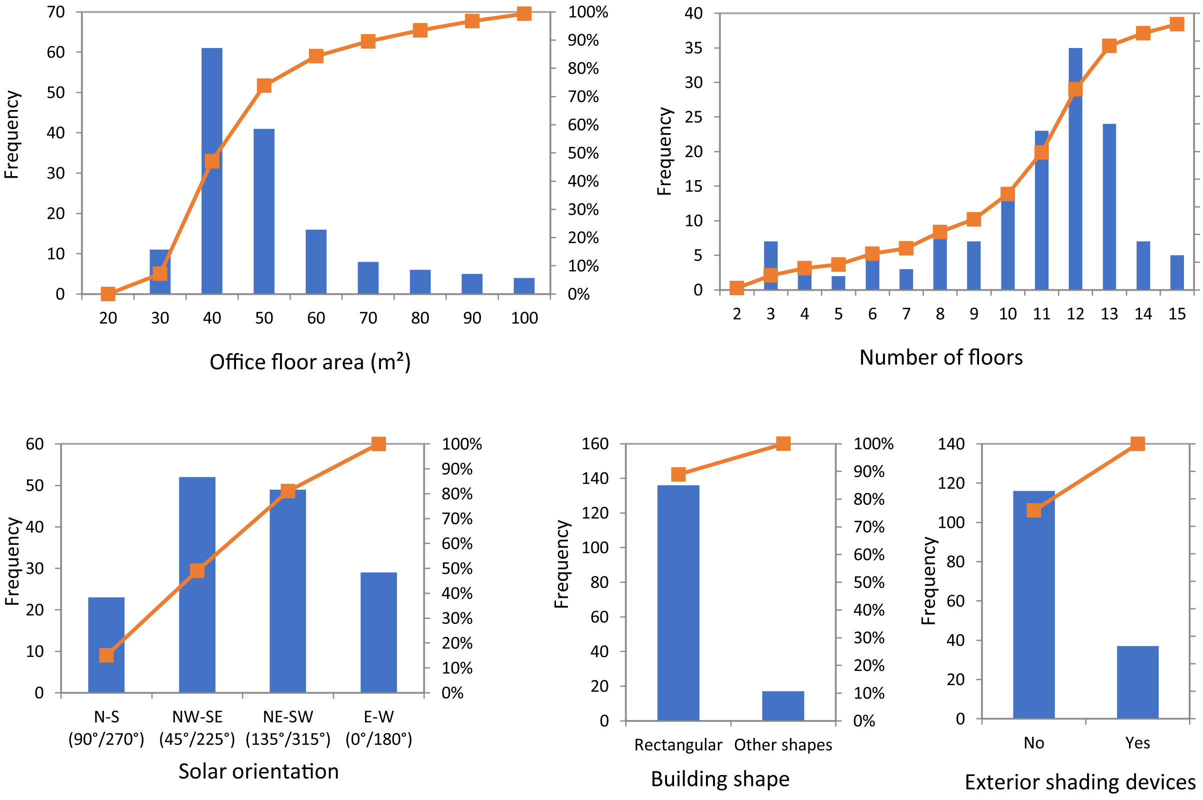

Fig. 3. Typical construction practices from the real buildings sample: geometry characteristics (as is).

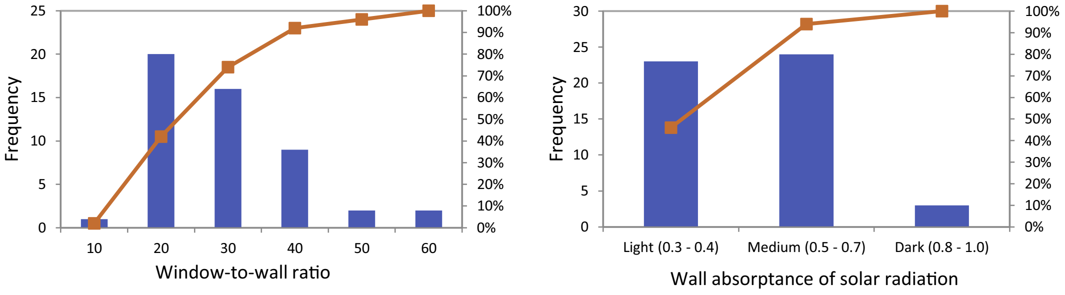

Fig. 4. Typical construction practices from the real buildings sample: envelope characteristics (as is).

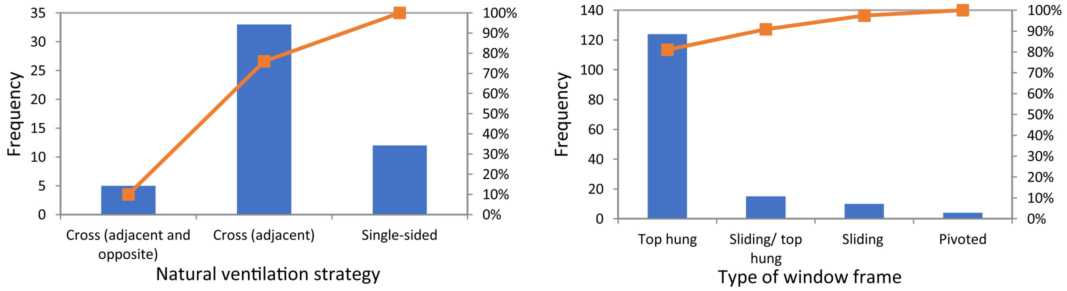

Fig. 5. Typical construction practices from the real buildings sample: natural ventilation characteristics (as is).

subtropical climate of the city of Sao Paulo, Brazil, and to point out which are the most and least influential variables affecting the building energy performance. The comparison between the three methods also aimed to analyse the contribution of each one to the energy performance analysis.

3.2.1. *Local sensitivity analysis: one-factor-at-a-time (OFAT)*

Fig. 6 depicts the impact of minimum and maximum values of each input variable on the annual thermal loads, resulting from the OFAT sensitivity analysis. We can observe the possibility of improving typical construction design practices, from the point of view of energy performance, by observing the difference between the base case model (grey line) and minimum thermal loads (orange bar). The blue bar represents the maximum thermal load. The base case model resulted in an annual thermal load of 39 kW/(m^2.year).

The OFAT approach allows us to understand the performance and influence of each parameter on the thermal loads results. The WWR set as 70% (maximum value of the range) was the parameter that resulted into the highest thermal load value, followed by the wall thermal transmittance of 0.3 W/(m^2.K) (minimum value of the range). Decreasing the WWR from 70% to 10%, it represents an annual thermal load reduction of 56 kW/(m^2.year), and comparing it with the base case model, it represents an annual thermal load reduction of 38 kW/(m^2.year). The result presented for wall thermal transmittance showed that commercial buildings located in Sao Paulo, Brazil, require less insulation to dissipate the internal and solar gains from interior to exterior. The annual thermal load difference between a wall thermal transmittance of 0.3 W/(m^2.K) to 3.7 W/(m^2.K) is 35 kW/(m^2.year). The base case model SHGC is another typical construction design practice that presented a reduction in the annual thermal load when compared to the minimum value of the input variables. Changing the clear glass to a high performance one can reduce the annual thermal loads in 29 kW/(m^2.year), approximately 25%.

Fig. 7 presents the effects of each input variable on the building annual thermal loads and a comparison with the base case model. According to the figure, it is possible to observe the behaviour of each input parameter in the annual thermal loads result; therefore, combined effects are not considered. The annual thermal loads increase as the values of the input parameters solar absorptance, SHGC and WWR also increase, showing a positive correlation. An increase in their value leads to an increase in the annual thermal loads, since these parameters are associated with higher energy consumption for cooling. The window opening effective area and the shading devices were the only parameters with a significant negative correlation.

For the input parameters window opening effective area, shading device, thermal capacity, wall thermal transmittance and height the annual thermal loads decrease as the input values increase. The input parameter floor height presented practically the same annual thermal loads result for input each value assumed. The results in Fig. 7 also show the behaviour of the base case model for each input parameter, previously described in Table 2.

Table 8 presents the Sensitivity Index (SI) of each variable parameter, which measures its impact over the output variable. The most influence input parameter on the annual thermal loads is the glazing SHGC, followed by the WWR and the window opening effective area.

3.2.2. *Screening analysis: morris*

Fig. 8 shows the results from the Morris sensitivity analysis. The location of a point compared to the dotted wedge provides information about the characteristics of the design parameter. The points located inside the wedge, i. e., the floor height, the thermal capacity and the thermal transmittance of exterior walls, have mainly a correlated or/and a non-linear impact on the output. The point placed outside and far from the wedge, which corresponds to the window opening effective area, shows a linear impact over the output, which means that a change in this design parameter would give a proportional change on the output. The points located close to the lines of the wedge, which are the WWR, the glazing SHGC,

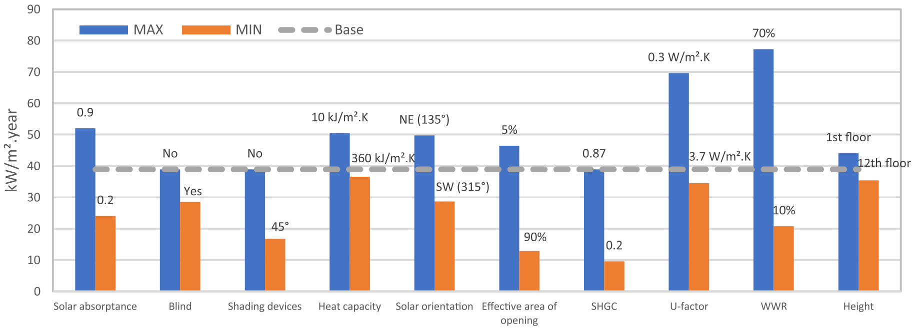

Fig. 6. Impact of minimum and maximum values of input parameters on the energy demand (as is).

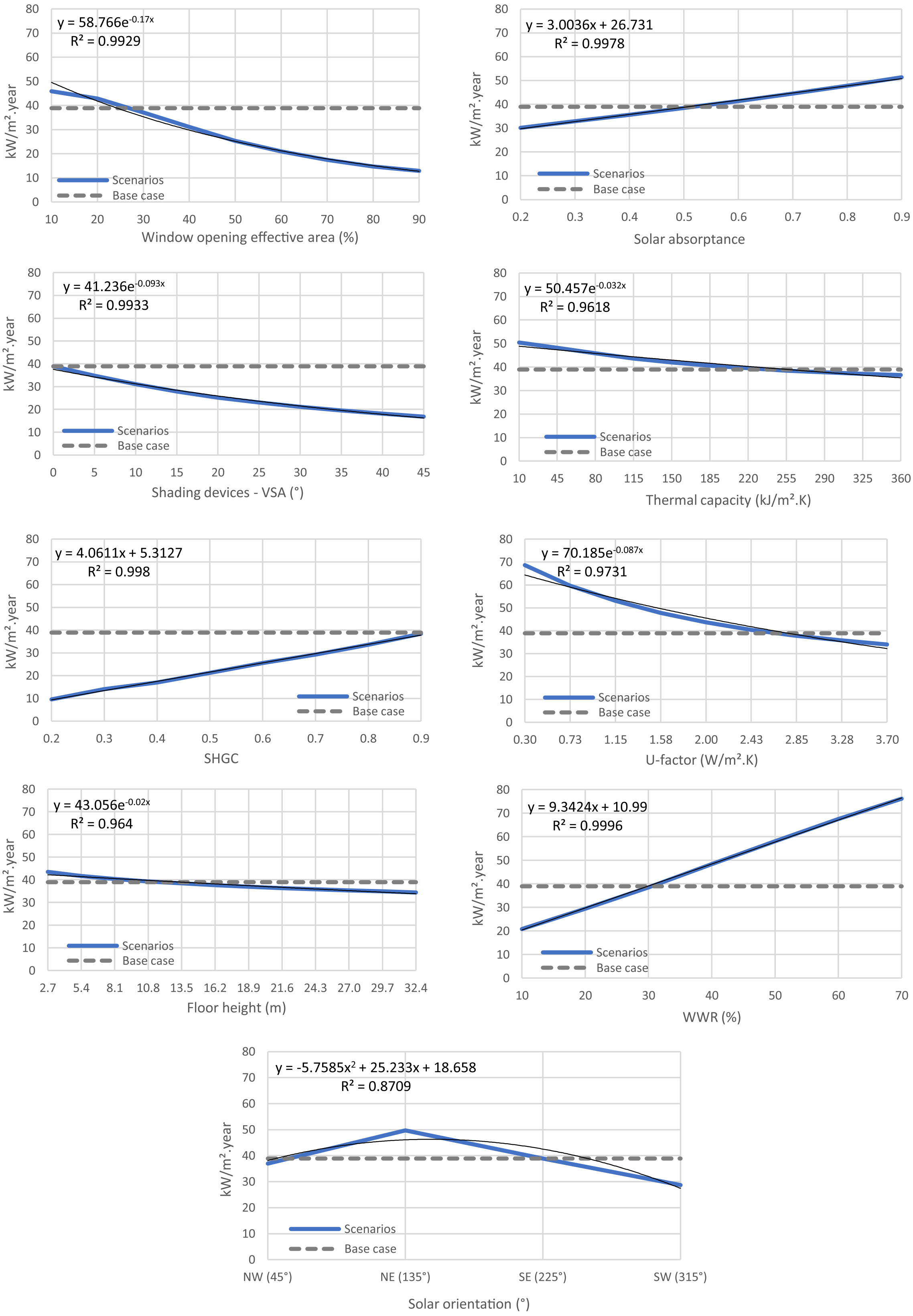

Fig. 7. Effects of each input variable on the annual building energy demands (as is).

Table 8
Sensitivity index (SI) for annual thermal loads (kW/m^2.year) – OFAT sensitivity analysis.

Input variable	SI (%)
SHGC	75
WWR	73
Window opening effective area	72
Exterior shading devices	57
Solar absorptance	54
U-factor	50
Solar orientation	42
Thermal capacity	28
Blind	27
Floor height	20

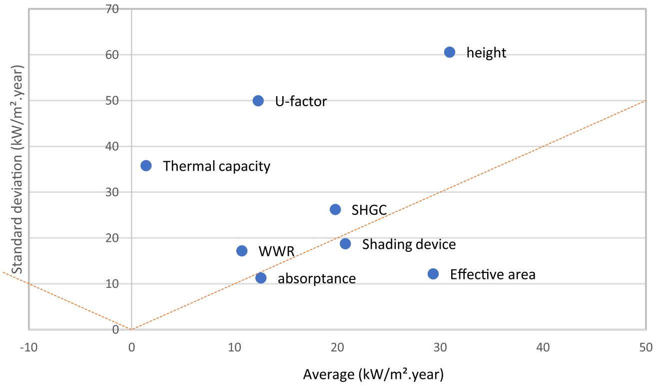

Fig. 8. Influence of design parameters on the annual thermal loads – Morris analysis (as is).

the solar absorptance of exterior walls and the exterior shading devices, are a combination of the two above cases, which means that those variables could have either a linear or a non-linear behaviour.

A ranking of the input variables' influence on the sensitivity of the thermal loads is listed in Table 9. The floor height is highlighted as the most influential design parameter for annual thermal loads. On the other hand, the wall thermal capacity parameter was ranked with the lowest average value.

3.2.3. Global sensitivity analysis: Monte Carlo and regression analysis

Fig. 9 presents box plots from the results of the Monte Carlo analysis. The parameters window opening effective area, shading devices and SHGC were the most influential on the annual thermal loads results. For these parameters, the increase from minimum to maximum values presented a significant influence in the median result. The parameter window opening effective area showed a decrease of 23 kW/(m^2.year) by comparing 5–21% to 73–90%. The parameter shading devices showed a decrease of 13 kW/(m^2.year) by comparing 0–8(°) to 32–45(°), and the parameter SHGC showed an increase of 16 kW/(m^2.year) by comparing a high performance glazing with a simple glazing. For all other parameters, the median result is practically the same for each input value. Therefore, the maximum annual thermal load values vary from minimum and maximum value of input parameters, i. e., the wall thermal transmittance of 0.3–0.97 (W/m^2.K) corresponds to a maximum thermal load of 98 kW/(m^2.year); and the wall thermal transmittance of 3.02–3.70 (W/m^2.K) corresponds to a maximum thermal load of 76 kW/(m^2.year). The difference is 22 kW/(m^2.year) (22%).

Table 9
Importance of design parameters for annual thermal loads (kW/m^2.year) - Morris sensitivity analysis.

Input variable	μ (average) – kW/(m^2.year)
Floor height	31
Window opening effective area	29
Exterior shading devices	21
SHGC	20
Solar absorptance	13
U-factor	12
WWR	11
Thermal capacity	1

The boxplots in Figs. 10 and 11 show combinations between interrelated parameters that presented the greatest impact on the overall results. The parameters selected are window opening effective area, shading devices and SHGC. The minimum and maximum values of each input parameter were considered, to observe their performance with combined effects.

Fig. 10 represents the combination between shading devices and window opening effective area. For a shading device of minimum size, the window opening effective area of 5–21% represents a significant influence on the annual thermal loads – median of 54 kW/(m^2.year). Increasing the shading device size reduced the median to 28 kW/(m^2.year) (difference of 48%). The same performance is observed by fixing the minimum and maximum values for the window opening effective area parameter. For a vertical shadow angle of 0–8°, the median is reduced from 48 kW/(m^2.year) (window opening effective area of minimum size) to 15 kW/(m^2.year) (window opening effective area of maximum size), a 69% difference. Fig. 10 shows a clear correlation among window opening effective area and shading devices, i. e., a combination of shading devices and high window opening effective area have the highest influence for the best energy performance.

Fig. 11 shows the combination between SHGC and shading devices. Regarding the results with best performance, it can be noticed that the influence of solar shading varies widely. Results demonstrate the importance of adopting solar shading with simple glazing (SHGC = 0.76–0.90). However, by considering high performance glazing (0.20–0.33), the influence of the solar shading on the annual thermal loads is reduced. A simple glazing leads to a higher degree of interaction with the outdoor environment; therefore, changes in the shading devices have considerable impact on the building energy performance.

The behaviour of the regression model for annual thermal loads is further analysed in Table 10. Standardized regression coefficients (β) are ordered from top to bottom, based on the parameter's influence on annual thermal loads. The overall model fit of adjusted R^2 (0.781) and the p-value (<0.001) showed significant in predicting 78.1% of the variance in annual thermal loads (kW/m^2.year).

Among all independent parameters, the window opening effective area has the highest SRC value (−0.654), followed by SHGC (0.423) and exterior shading devices (−0.325). The standardized coefficients results judge how statistically significant the parameter is. However, the best building energy performance will vary depending on the combination among other building characteristics.

4. Discussion

As can be seen from the OFAT results (Fig. 7), with the increase of the shading devices' size, the floor height, the thermal capacity and the thermal transmittance of exterior walls, the annual thermal loads decreased exponentially. The nonlinear behaviour of those variables could make the use of the OFAT analysis misleading, with possible interference on the results of the sensitivity index. The annual thermal loads also decreased with the increase of the

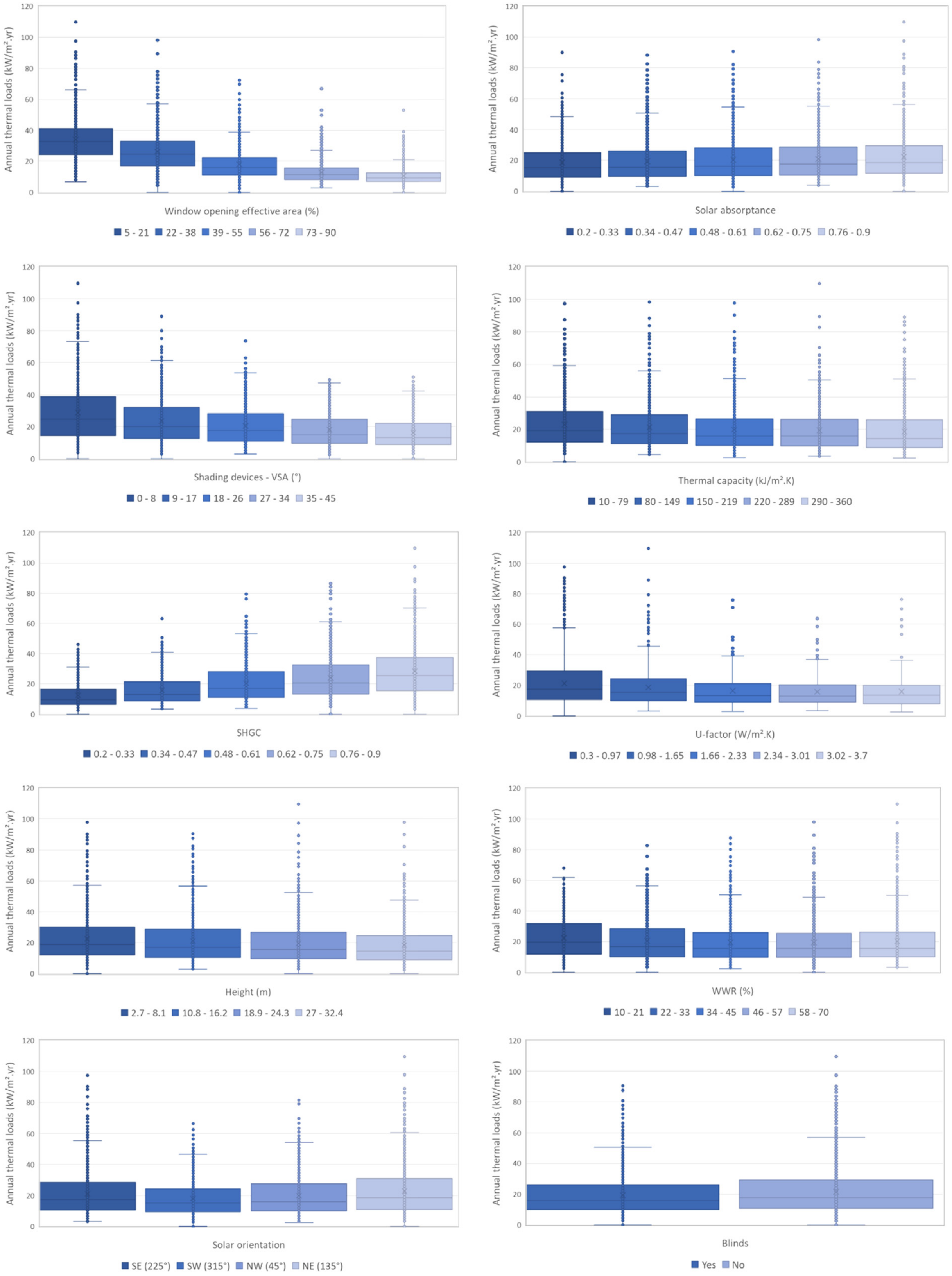

Fig. 9. Box plot of annual thermal loads for each input variable (as is).

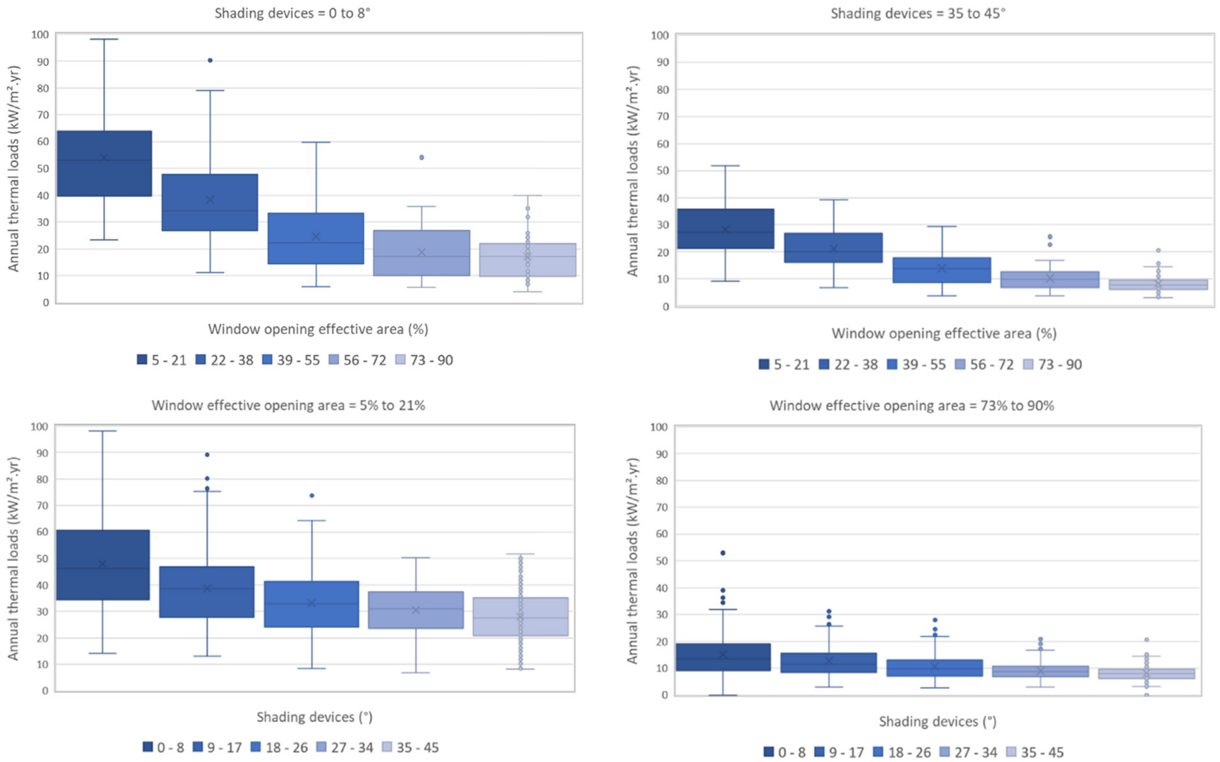

Fig. 10. Box plots of annual thermal loads for window opening effective area (%) versus exterior shading devices (°) (as is).

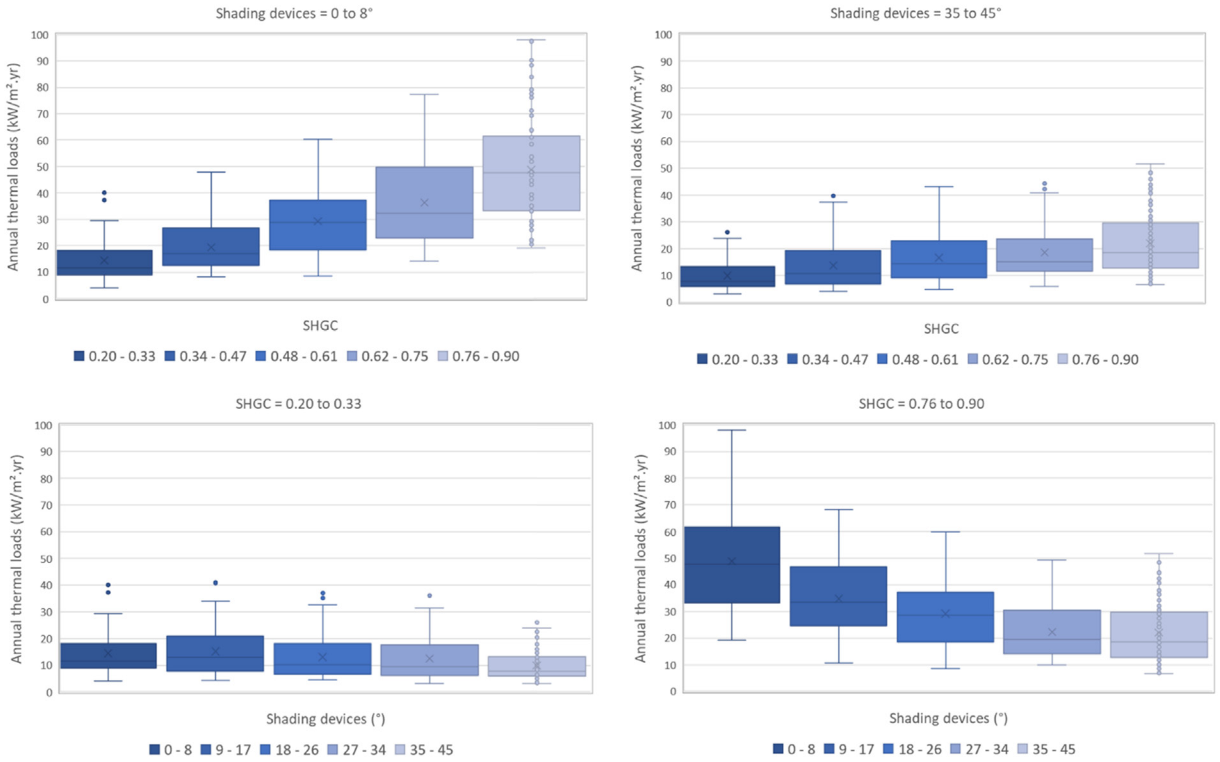

Fig. 11. Box plot of annual thermal loads for glazing solar heat gain coefficient versus exterior shading devices (°) (as is).

window opening effective area. Despite the exponential tendency line obtained from the results of the OFAT analysis being this variable's best fit ($R^2 = 0.9929$), a linear correlation could also be assumed ($R^2 = 0.9781$). Changing the room solar orientation also resulted in a nonlinear and complex behaviour, regarding energy performance. In this case, the use of local sensitivity analysis may

Table 10
Annual thermal loads multivariate regression model.

Independent parameters	Adjusted $R^2 = 0.781$			
	Unstandardized coefficients		Standardized coefficients	
	B	Error (kW/m^2.year)	β	Error (kW/m^2.year)
Window opening effective area	38.822	0.449	−0.654	0.005
Exterior shading devices	−35.140	0.281	−0.325	0.005
SHGC	−0.339	0.005	0.423	0.005
Thermal transmittance	27.495	0.341	−0.140	0.005
Height	−2.783	0.104	−0.122	0.005
Thermal capacity	−0.468	0.020	−0.113	0.005
Solar absorptance	−0.015	0.001	0.105	0.005
Blinds	6.850	0.342	−0.078	0.005
Solar orientation	−2.075	0.140	−0.060	0.005
WWR	−0.008	0.001	−0.059	0.005

also be thoroughly misleading. The annual thermal loads linearly increased with the increase of the input variables WWR, SHGC and solar absorptance of the exterior wall. R-squared was higher than 0.999 for the three variables. As it can be depicted from Fig. 6 and Table 8, the variables SHGC, WWR and window opening effective area demonstrated the highest impact on the energy performance results (in order of importance).

One disadvantage of the Morris sensitivity analysis method (Fig. 8) is that it cannot quantify the effects of the input factors over the output, but just characterize/describe their behaviour. Results from this analysis showed a linear behaviour for the window opening effective area, confirming the assumption made in the OFAT analysis. The nonlinear behaviour of the floor height, the thermal capacity and the thermal transmittance of exterior walls could also be confirmed. The analysis of the importance of design parameters over the annual thermal loads results pointed out the floor height, the window opening effective area and the exterior shading devices as the variables with highest impact on energy performance (in order of importance). However, the floor height presents an opposite performance by applying OFAT analysis – lowest SI value. The parameter WWR, one with the highest SI in the OFAT analysis, also presented an opposite performance by applying Morris sensitivity analysis, appearing as one of the variables with least influence over the results. Nevertheless, it is important to be aware that not all ranking factors are created equal.

Results from the Monte Carlo analysis (Figs. 9–11) showed higher impacts over the annual thermal loads results for the variables window opening effective area, exterior shading devices and SHGC. When comparing the interrelationship between exterior shading devices and window opening effective area (Fig. 10), it can be observed that by increasing the shading device's VSA the annual thermal loads decrease proportionally for all percentages of window opening. Conversely, the impact of the device's VSA is low when using high percentages of window opening. A similar relationship can be observed between exterior shading devices and the glazing SHGC (Fig. 11), since by increasing the device's VSA the annual thermal loads increase proportionally for all SHGC ranges. Again, the impact of the shading device's VSA is low when using low SHGC. Results for standardized regression coefficients (β) (Table 11), obtained from the regression analysis global sensitivity method, showed that the variables window opening effective area, exterior shading devices and glazing SHGC were the most significant predictors (in order of importance). The variables blinds, solar orientation and WWR were found to be not so significant. Results from the OFAT analysis could be confirmed for the window opening effective area and the glazing SHGC. On the other hand, results from the Morris analysis could also be confirmed for the window opening effective area and for the exterior shading devices. Likewise, the WWR appeared as one of the variables with least influence over the results.

Results from the regression analysis confirmed the strong correlation of the window opening effective area with the WWR. This last parameter, of major impact in the energy performance of mechanically ventilated buildings (Hou et al., 2016), had its importance diminished in MMV buildings, since the increase in the total window opening area diminishes the negative impact of the increase in the WWR. This finding explains the high impact of the WWR on energy performance outputs resultant from OFAT analysis, since the correlation between design parameters is not considered, and, in contrast, its low impact resultant from Morris and regression analyses.

5. Conclusion

This study aimed to assess the influence of building envelope parameters on the energy performance of MMV office buildings located in the humid subtropical climate of the city of Sao Paulo, Brazil, representing typical construction design practices. Different sensitivity analysis techniques were applied, aiming to obtain relative parameter sensitivity to annual thermal loads and identify the most and least influential variables.

A base case model was defined, based on a sample of 153 mixed-mode office buildings, and compared with solutions adopted by technical studies from the literature. This first comparison showed that research studies regarding the energy performance of cross ventilated mixed-mode office buildings are lacking, despite it being the most frequent natural ventilation design solution in practice. Three sensitivity analysis methods were then applied to the model: OFAT, Morris and Monte Carlo. The OFAT analysis showed that an insulated envelope increases the annual thermal loads, for the base case model considered. The Morris analysis confirmed the assumptions described in the OFAT analysis for linear and nonlinear parameters behaviour. The Monte Carlo analysis allowed to understand the correlation between parameters with higher impact on the annual thermal loads. Results from the three methods confirmed the importance of the window opening effective area on the energy performance of MMV office buildings. Nevertheless, this parameter has still been poorly explored in specialized literature. Also, the WWR itself presented low impact on energy performance, since higher values of WWR also implies larger opening areas for natural ventilation. Instead, a combination of shading devices and high window opening effective area had the highest influence for the best energy performance.

The multivariate regression model application showed significant in predicting 78.1% of the variance in annual thermal loads. The accurate determination of annual thermal loads into MMV office buildings can be used to optimize the envelope characteristics based on a combination of input data and the building geometry. The annual thermal loads vary as a function of a combination of different parameters. Hence, the sensitivity results reinforce the importance of defining correctly input parameters and their range, in order to achieve success on the assessment of building energy performance. Also, the weather condition and building characteristics are important variables to consider, in order to obtain a more precise estimate. Hot climates with dense urban contexts, such as the present study, should carefully consider passive design strategies according to local environment (Lee and Won, 2017). MMV cellular office buildings consist on a building design typical of other regions in Brazil (Alves et al., 2018) and several other countries (Wei et al., 2013; Roetzel and Tsangrassoulis, 2012; Elharidi et al., 2017). Therefore, findings from this study could also be applied to other locations, provided that similar climatic environment and urban context are taken into account.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.06.216.

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