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Sensitivity analysis on daylighting and energy performance of perimeter offices with automated interior roller shades

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ABSTRACT

Utilization of daylight in perimeter office spaces introduces opportunities for energy savings. Daylighting performance is affected by many interfacing factors such as glazing size and properties, shading properties and control, interior surface reflectivity, climate and orientation. These factors also affect the thermal loads and hence the energy performance of the space. This paper investigates the sensitivity of daylighting and energy performance to the above mentioned factors based on simulations using a comprehensive model developed in a previous study. The design factors with more significant impact were identified using the MC-LHS method for uncertainty analysis and the variance-based FAST method for further sensitivity analysis. The results can be expanded to provide recommendations to building designers at the design and operational phases, for both new buildings and retrofit applications.

1. INTRODUCTION

High energy requirements and limited energy resources have sparked a lot of research activities concentrating on early building design stage for energy saving purposes. Previous studies used approaches based on evaluation of several alternative design options to identify the better solution (Mihalakakou and Ferrante, 2000) or analysis of influence coefficients in terms of a base case to determine the important design parameters (Lam and Hui, 1995; Tavares and Martins, 2007). Recently, more advanced sensitivity analysis approaches have been employed in determination of the most important parameters in relation to building performance. Heiselberg et al. (2009) used the elementary effects method to investigate which design parameters are the most important among the 21 selected factors to change in order to reduce the primary energy consumption. Mechri et al., (2010) employed the Monte Carlo method with Latin Hypercube Sampling (MC-LHS) and the Analysis Of Variance-Fourier Amplitude Sensitivity Test method (ANOVA-FAST) for uncertainty and sensitivity analysis of heating and cooling energy needs –the envelope transparent surface ratio was distinguished as the most significant factor. In some studies (Dominguez-Munoz et al., 2010; Yidiz and Arsan, 2011; Yildiz et al., 2012), the MC-LHS method was also used to calculate the sensitivity indices such as SRC and SRRC given that the model coefficient of determination is higher than 0.7 (Saltelli et al., 2004). Windows have gained enough importance as an influential envelope element. Usually one or more factors related to window including transparent surface ratio, U-value and solar heat gain coefficient were considered in analysis. However, those parameters were used only for thermal considerations. Utilization of daylight in perimeter office spaces introduces opportunities for energy savings (Shen and Tzempelikos, 2012). The daylighting performance is affected by many interfacing factors such as glazing size and properties, shading properties and control, room aspect ratio and orientation. These factors also affect the thermal loads and hence the energy performance of space. In order to improve the overall performance via most effective approach in design, a sensitivity analysis should be applied to an integrated building model, especially when dynamic façade controls are involved. This paper presents a comprehensive global uncertainty and sensitivity analysis of daylighting and energy performance for private offices with automated interior roller shades using an advanced transient simulation model. Studied performance indices include useful daylight illuminance, annual lighting, heating and cooling demand and annual source energy consumption. The uncertainty analysis is based on MC-LHS method showing the possible ranges in these performance indices. The sensitivity analysis uses a variance-based method in the extended FAST implementation. First order and total order effects of each studied parameter were calculated to determine the building parameters that have the most significant impact on the performance indices.

2. UNCERTAINTY AND SENSITIVITY ANALYSIS

Mathematical methods for uncertainty and sensitivity analysis are well-known (Saltelli et al., 2008). In the past decades, uncertainty and sensitivity analysis have become popular in various engineering fields. In building physics practice, uncertainty analysis provides the expected distribution of possible values for a model response following the variations of the input parameters within their respective distributions and ranges. The purpose of sensitivity analysis is to apportion the uncertainty in the model response to different sources of uncertainty in the model input. It distinguishes itself as a good practice by revealing which of the input parameters has a significant impact on the output so as to direct research priorities to factors that are responsible of the biggest output variability, and eventually achieve the design aim of energy saving.

There are many techniques that can be applied in uncertainty analysis. Among those, the Monte Carlo technique is based on performing multiple evaluations with randomly sampled points of model inputs according to their corresponding probability density functions, and then using the results of these evaluations to determine the uncertainty in model predictions. If the model is linear or at least monotonic to each of its input, these evaluations can also be used to determine the contributions of the inputs to this uncertainty by calculating SRC, SRRC or other indicators. In the meantime, several methods have also been developed for sensitivity analysis. For example, differential method (Lomas and Eppel, 1992), Factorial method (Furbringer and Roulet, 1995), Morris method (Morris, 1991) and variance-based methods are the often used approaches. In general, for a moderate number of factors and a model with short execution time, the variance-based methods are ideal.

3. METHODOLOGY

3.1 Integrated Building Model

The integrated building model developed in a previous study (Shen and Tzempelikos, 2012) is used here with two improvements. The model is composed of a daylighting calculation part and a thermal calculation part, which run simultaneously and coupled by façade design parameters as well as by shading and lighting controls. In this study, equations based on EnergyPlus (2007) are used in the current model to calculate the effective values of glazing and shading properties taking into account inter-reflections between glass and shades. In the thermal calculation, the explicit finite difference thermal network approach is used to model the transient thermal response of the studied space. The current model tracks the percentage of the transmitted direct solar radiation falling on each surface. The transmitted diffuse solar radiation goes to each surface according to the respective area ratio. After the first absorption, the reflected part becomes diffuse radiation and is finally absorbed by each surface in terms of their respective area-absorptance weighting factors. Figure 1 illustrates a schematic of the heat transfer mechanisms near a façade with a double-glazed window and an interior roller shade. The opaque walls are discretized into two surface nodes and one mass node connecting with a capacity (if the wall has a mass layer). The glazing system has one node for each of its glass pane. The interior roller shade has one node to represent the entire surface. At each thermal node, the heat balance on each node is solved for every calculation time step with equation (8).

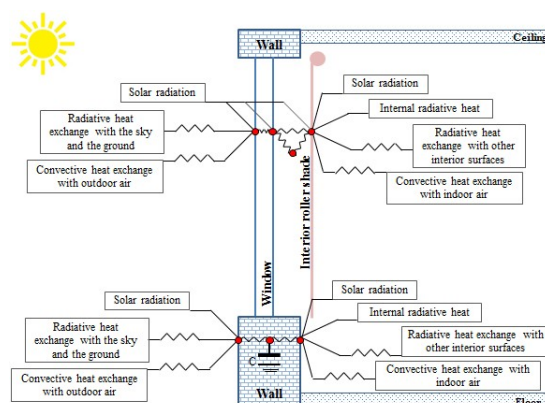


Figure 1. Heat flows, solar gains and thermal nodes near a façade with a double-glazed window and an interior roller shade.

$$C_i \frac{T_{i,p+1} - T_{i,p}}{\Delta t} = \sum \left(\frac{T_{j,p} - T_{i,p}}{R_{j,p}} \right) + S_{i,p} \quad (8)$$

where c_p is the specific heat, J/kg·K; ρ is the density, kg/m³; Vol is the volume of the mass node (i), m³; T is temperature, °C; p represents the time step; Δt is the calculation time step, s ; j represents all nodes connected to node i ; $R_{j,p}$ is the total thermal resistance between nodes i and j , K/W, C_i is the capacitance of node (i), J/K·m²; and S_i is total heat input to node (i), W. The convection heat transfer coefficients are calculated with DOE-2 convection model (EnergyPlus, 2007). Radiation heat transfer between all surfaces is modeled in detail using non-linear heat transfer coefficients (Siegel and Howell, 1972).

3.2 Uncertainty analysis

The Monte Carlo (MC) technique is used for uncertainty analysis in this study. One of the most important steps in MC analysis is the generation of a sample according to the distributions and ranges of studied factors. Various sampling procedures are available: random sampling, stratified sampling and quasi-random sampling. Latin Hypercube Sampling (LHS) is a particular case of stratified sampling. The range of each input factor is divided into s ($s > 2$) intervals of equal marginal probability, and within each interval one observation is made randomly. This sampling method has the advantage of representing all portions of a factor distribution by input values and has been used in this study. The number of executions (n) is recommended as no less than 1.5 times of the number of factors (k) (JRC, 2008). The uncertainty of the output may be represented with a frequency graph or histogram. The coefficient of variation (v), which is the ratio of the standard deviation (σ) to the mean value (μ) given by Eqs. (9) and (10) is also a good indicator to evaluate the dispersion of the outputs.

$$\mu = \frac{1}{n} \sum_{i=1}^n y_i \quad (9)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (y_i - \mu)^2} \quad (10)$$

3.3 Sensitivity analysis

Building physics problems are complex. The model used in this study to simulate the integrated building performance is neither linear nor monotonic. So the variance-based method is preferred because variance-based methods can cope with non-linear and non-monotonic models and appreciate the interaction effects among input factors. The currently most efficient variance-based measure available is the extended FAST method. This measure features a very rapid convergence and can compute the first-order sensitivity indices (S_i) and total-order indices (S_{Ti}) using the same sample set. These sensitivity indices are defined on the expected value (E) and the variance (V) of an output $Y(X_1, X_2, \dots, X_k)$ as:

$$S_i = \frac{V[E(Y|X_i)]}{V(Y)} \quad (11)$$

$$S_{Ti} = \frac{E[V(Y|X_{-i})]}{V(Y)} = 1 - \frac{V[E(Y|X_{-i})]}{V(Y)} \quad (12)$$

S_i represents the main effect contribution of the i^{th} input factor to the variance of the output. It has a value always between 0 and 1. The difference between S_i and S_{Ti} is a measure of how much the i^{th} input factor is involved in interactions with any other input factors. If a factor is non-influential, it will have a very small value of S_{Ti} and can be fixed at any value within its distribution. This is very beneficial to simplify the model and speed up further study such as optimization analysis. For fully additive models, the sum of S_i is equal to 1 and less than 1 otherwise. The sum of all S_{Ti} is always greater than 1 (equal to 1 for perfectly additive model).

In this study, the variance-based sensitivity analysis is performed in extended FAST implementation. The classic FAST method was introduced in the 1970s (Cukier et al., 1978) to compute only the first-order sensitivity indices. Later, Saltelli et al. (1999) improved it to extended FAST method which is also capable of computing higher order and total order indices. More details about the FAST can be found in Saltelli et al (2004; 2008). This study uses the free and powerful software SimLab2.2 (JRC, 2008) to generate sample set and compute the sensitivity indices.

4. CASE STUDY

In this study, the uncertainty and sensitivity analysis is applied to a typical private office space, located in Philadelphia, with automated interior roller shade as a case study. The space has a floor area of 16 m² and a height of 3 m. The interior roller shade is controlled to automatically close when incident beam radiation on the façade is higher than 20 W/m² during office hours (9am-5pm) – and they are kept closed during non-office hours. The shading schedules during working hours throughout the year can be expressed as the percentage of time during which shades remain open (Figure 2). The lighting system in the space is dimmable to compensate daylighting so as to reach the requirement of 500 lux on the work plane. The lighting system has a power density of 10 W/m² with 30% of the released heat convected to air directly (ASHRAE, 2009). The interior surface reflectances of the floor, ceiling and walls are 45%, 80% and 50% respectively. The exterior façade is composed of a brick layer (thickness: 10 cm), insulation and gypsum board with exterior absorptance of 60%. Occupant density in the space is 0.11 p/m², and sensible heat gain from each occupant is 76 W. Heating and cooling are always available throughout the year. The heating set point during office hours is 22 °C and 18 °C otherwise. The cooling set point during office hours is 24 °C and 26 °C otherwise. The heating system consumes natural gas (system efficiency 80%). The cooling system consumes electricity with (average COP=3.5). These values are typical and were used to convert to source energy use (source-site ratios are 3.34 for electricity and 1.047 for natural gas). Daylighting and energy performances are investigated in the uncertainty and sensitivity analysis. Evaluated performance metrics include useful daylight illuminance between 500-2000 lux (UDI), annual lighting, heating and cooling demand per unit floor area and annual source energy consumption per unit floor area. A detailed explanation of the selection of performance metrics can be found in Shen and Tzempelikos (2012).

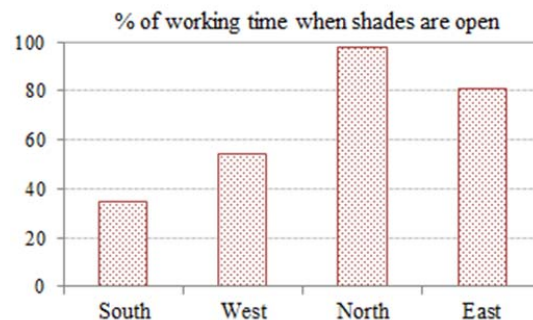


Figure 2. Percentage of annual time (working hours) during which automated shades remain open for the four major orientations.

4.1 Selection of design factors

There are many design parameters that affect the perimeter building performance. It is obvious that façade orientation has great impact on building performance (Nielsen et al., 2011). However, the orientation is not a factor that can be fully controlled –the analysis is performed for each main orientation in this study. From the study of Heiselberg et al. (2009), lighting system control is also an important factors influencing building primary energy consumption. The benefits of daylighting are mostly exploited when the lighting system is actively controlled. Therefore, this analysis is under the condition of continuously dimmable lighting system. Considered design parameters include: window size represented with window-to-wall ratio (*wwr*) or window-to-floor ratio (*wfr*), space aspect ratio (*ar*, room length to room depth), roller shade transmittance (*ts*), front side roller shade absorptance (*af*), back side roller shade absorptance (*ab*), façade insulation R-value (*ins*) and glazing type (*g*). For some factors, uniform distribution is a suitable representation of their possibility density function and range. On the other hand, some factors are discrete variables. Considering glazing properties as an example, the values of visible transmittance, solar transmittance, solar absorptance of each glass pane and glazing system conductivity are tightly related. Taking each of the properties as a factor and assigning them with a separate distribution is not a practical solution to the analysis. For this reason, these properties are grouped as one factor - glazing type - in this study. Table 1 summarizes the range and distribution of each design variable. The values are selected in order to represent the condition of a private office space.

Table 1. Description of studied design variables

Design variable	Symbol	Unit	Distribution	Range
Window size	wwr (wfr^*)	-	Uniform	[0.1, 0.9]
Space aspect ratio	ar	-	Uniform	[0.6, 1.5]
Shade transmittance	τ_s	-	Uniform	[0, 0.25]
Front side shade absorptance	α_f	-	Uniform	[0.05, 0.7]
Back side shade absorptance	α_b	-	Uniform	[0.05, 0.7]
Façade insulation R-value	ins	$m^2 \cdot K/W$	Uniform	[1.2, 2.8]
Glazing type	g	-	Discrete	1, 2, ... 6

* In the following sections, results are presented to wfr . Because area of the exterior façade is changing with the variation of ar , distribution and range of wwr is given and used to calculate the corresponding wfr .

In Table 1, insulation R-value is referring to DOE benchmark models (2008) and related standards. For the selection of glazing type, according ASHRAE (2009), 6 kinds of glazing are selected from WINDOW 6 (LBNL, 2011) to cover a range of glazing properties. The angular properties are used in the integrated building model for detailed simulation. Their properties at normal incidence angle are listed in Table 2.

Table 2. Properties of selected glazing system at normal incidence angle

Glazing type	Visible transmittance	Solar transmittance	1 st pane absorptance	2 nd pane absorptance	Coating emissivity	U-value ($W/m^2 \cdot K$)
<i>g-1</i>	0.786	0.607	0.167	0.113		2.689
<i>g-2</i>	0.717	0.473	0.337	0.086	0.2	1.907
<i>g-3</i>	0.647	0.307	0.396	0.031	0.04	1.667
<i>g-4</i>	0.482	0.313	0.437	0.051	0.11	1.793
<i>g-5</i>	0.384	0.19	0.53	0.021	0.062	1.705
<i>g-6</i>	0.361	0.185	0.327	0.023	0.043	1.668

4.2 Results and discussion

4.2.1 Uncertainty analysis. Based on the seven selected design parameters, the MC-LHS method is employed to obtain the mean values, the standard deviations and coefficients of variation of the useful daylight illuminance (500-2000 lux), lighting, heating and cooling demand and source energy consumption for each orientation. A large enough sample with 140 runs is generated and executed to obtain their values. Table 3 shows these information for the first three building performance.

Table 3. Mean, standard deviation and coefficient of variation of UDI, lighting, heating and cooling demand of the studied private office for four main orientations.

Orientation	UDI (%)			Lighting demand ($kWh/m^2 \cdot year$)			Heating demand ($kWh/m^2 \cdot year$)			Cooling demand ($kWh/m^2 \cdot year$)		
	μ	σ	v (%)	μ	σ	v (%)	μ	σ	v (%)	μ	σ	v (%)
South	37.9	22.3	58.7	10.2	6.3	62.1	22.6	5	22.2	41.9	13.4	32
North	52	21	40.3	5.7	3.8	68	31.5	6.5	20.6	31.7	9.4	29.7
East	47	18.4	39.2	7.1	4.3	59.9	28.2	5.9	20.8	39.4	13.3	33.8
West	43.7	20.2	46.3	8.4	5.3	63.2	27.9	6	21.5	43.1	14.5	33.8

As shown in Table 3, lighting demand has the highest coefficient of variation up to over 60%, followed by UDI (40%-60%) and cooling demand (around 30%), and then heating demand around 20%. The high values of coefficient of variation highlight large dispersions of the outputs, indicating that decisions should be made very carefully in the early design stage to ensure that the various building performance indices remain in the preferred range. Comparing the four orientations, south and west show higher variation coefficient in terms of UDI while north and east show lower and similar variation coefficient. For lighting, heating and cooling demand, the four main orientations have similar values of variation coefficient. Compared to the above three building performance, source energy consumption shows lower coefficient of variation. Figure 3 illustrates the statistic characteristics of annual source energy consumption per unit floor area for four main orientations. The coefficients of variation for source energy consumption are lower than

20% for all four main orientations. South and west facades show similar source energy consumption in terms of the median, maximum and minimum values. The variation coefficient for south is higher than west since the middle 50 quartiles for south covers a wider range. North and west facades show similar coefficient of variation while north requires less source energy. The large dispersion of all evaluated building performance calls for a further analysis to identify the most influential factors. Because the different orientations show different uncertainty characteristics, the sensitivity analysis needs to be performed for every main orientation.

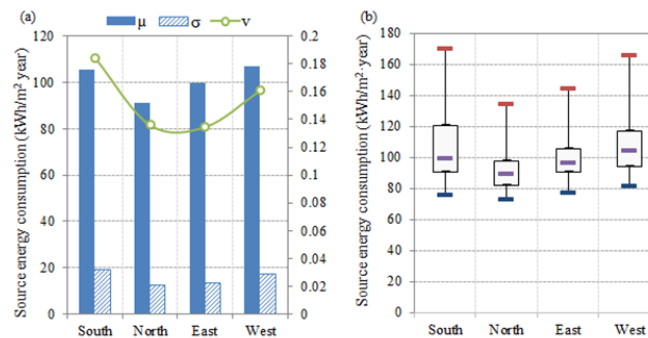


Figure 3. (a) Mean, Standard deviation and coefficient of variation of source energy consumption and (b) Boxplot of source energy consumption showing maximum, upper quartile, median, lower quartile and minimum values for four main orientations.

4.2.2 Sensitivity analysis. Using the extended FAST method, a sample set with length equal to 460 data is generated and executed. The first order and total order sensitivity indices are computed for all the studied building performances and four main orientations.

UDI and lighting demand. Figure 4 shows the sensitivity indices of the seven studied design factors in terms of UDI performance for four main orientations. Window-to-floor ratio has dominating influence on UDI performance with high values for both first order and total order indices. For south and west, shade transmittance also has significant influence on UDI performance indicated by the first order indices. For north and east facades, first order indices show that shade properties almost have no impact on UDI. This can be explained by the longer shade open time for north and east than south and west. Glazing type does not have a significant impact on UDI for all orientations as seen from its first order indices. This is reasonable since for south and west, the effective transmittance of glazing-shade system is mainly depend on shading transmittance; and for north and east, transmitted daylight is high enough for most of the office hours. However, when total order indices are computed, glazing type is an important and influential factor for all orientations. It is reasonable to expect that the impact of glazing type is mostly involved in interactions with shading properties. For north and east, the front side shade absorptance shows much higher total order indices than first order indices. This is somewhat out of expectation and difficult to explain since the definition of UDI is an illuminance range (between 500 and 2000 lux). Low illuminance (lower than 500 lux) and high illuminance (higher than 2000 lux) will both result in low UDI values.

Heating demand and cooling demand. Figures 5-6 show the sensitivity indices of the seven studied design factors in terms of heating demand and cooling demand respectively for four main orientations. Window-to-floor ratio and glazing type dominate the variation of both heating demand and cooling demand. For heating demand, space aspect ratio is the third important factor for south, east and west, while space aspect ratio and façade insulation R-value are the two almost equally third important factors for north. It may be confusing that the façade insulation condition is not as important as expected. However, this can be explained by the studied case of a small private office with only one exterior façade. Solar radiation is doubtlessly a very important source of heat to buildings. This solar heat gain alleviates heating needs and deteriorates cooling needs. In this sense, shade transmittance should have important impact on heating demand and cooling demand. This is true for south but not for other orientations. A possible reason is that the incident solar radiation on south façade is high during the heating period, but much lower for other orientations; and in cooling period it is attributed to the longer sunshine time for south than other orientations during office hours (note that the set points are different for office hours and non-office hours). Internal gains which are inevitable in office spaces also play an important role.

Source energy consumption. For source energy consumption, the results are quite different. Although source energy consumption is calculated from energy consumption on lighting, heating and cooling, the relationship may not be applied to sensitivity indices. First, the energy consumption for lighting, heating and cooling is not independent. For example, if lighting needs increase, the cooling needs may also increase and the heating needs may decrease –this is considered in the transient building simulation model used. Figure 7 shows the sensitivity indices of the studied design factors in terms of source energy consumption for four main orientations. Window-to-floor ratio and glazing type are very important factors for all the four main orientations. For south and west facades, another important factor is the shade transmittance. For north facades, space aspect ratio and insulation conditions are also important. Front side shade absorptance is the third most important factor for east-facing rooms.

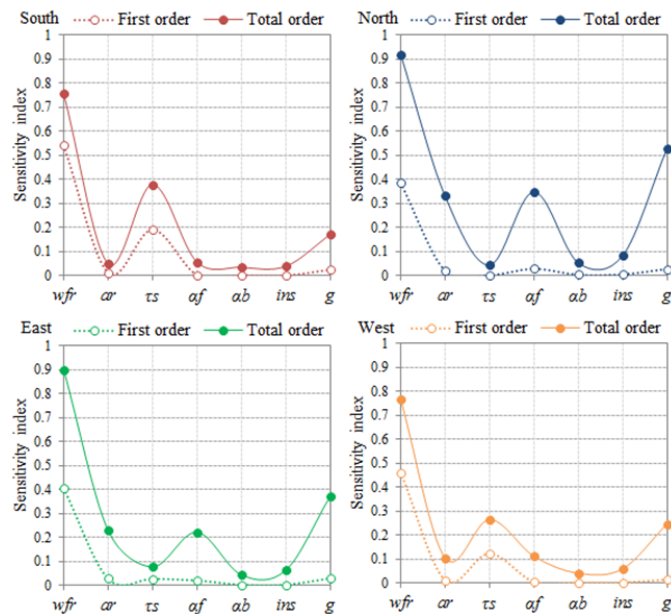


Figure 4. First order and total order sensitivity indices – UDI (500-2000 lux)

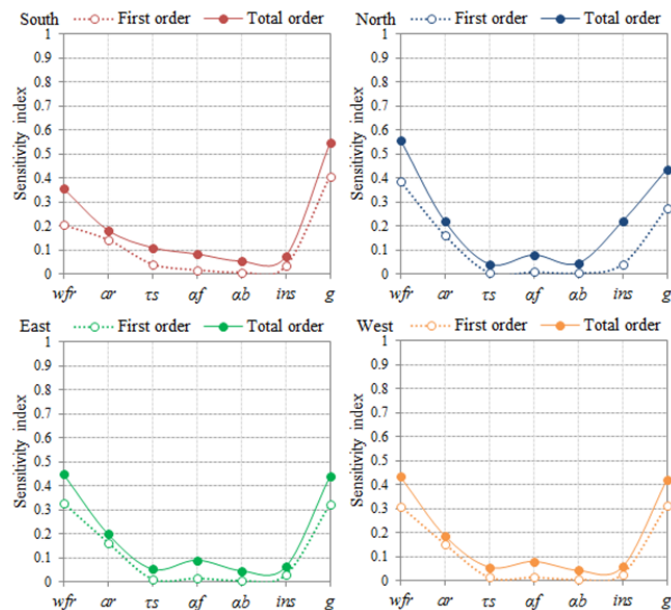


Figure 5. First order and total order sensitivity indices – heating demand (kWh/m²·year)

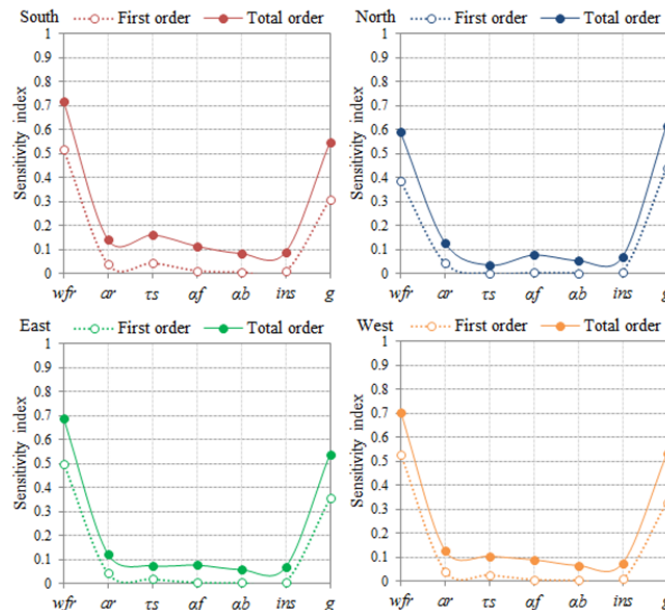


Figure 6. First order and total order sensitivity indices – cooling demand ($\text{kWh}/\text{m}^2 \cdot \text{year}$)

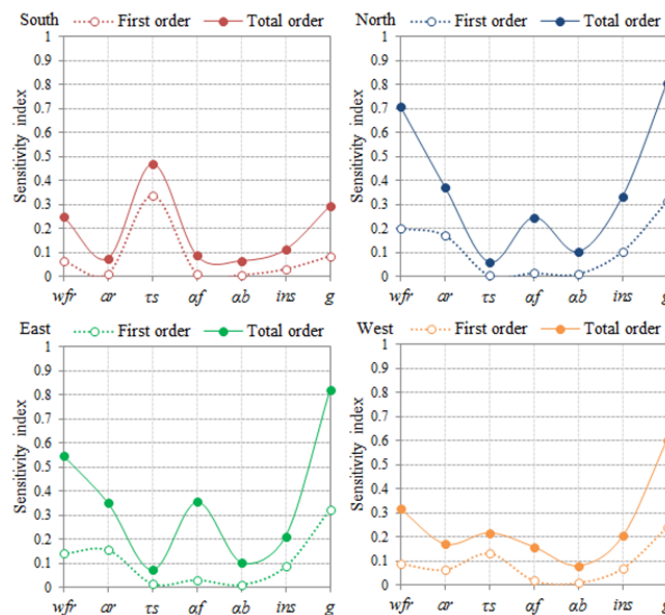


Figure 7. First order and total order sensitivity indices – source energy consumption ($\text{kWh}/\text{m}^2 \cdot \text{year}$)

After obtaining the importance indices of the studied factors, it is beneficial to estimate the variation of the source energy consumption to the inputs. The scatterplot is a suitable way to reveal the relationship between the model output and its inputs. Figure 8 shows the scatter plot of source energy consumption to some important factors for different orientations. For factors with discrete distribution like the glazing type, the box plot is preferred to illustrate the results. The relationship between source energy consumption and shown design parameters are well revealed. Such situation usually happens when there is a strong relationship between an input of great significance and output. Figure 8 (d) reveals that g-3 performs better in terms of space source energy consumption. This type of glazing has the characteristic of high visible transmittance but comparatively low solar transmittance as well as low coating emissivity (low U-value) and low solar absorptance. Because these glazing properties just mentioned are related with each other and

are not continuously available from market, it is more reasonable to compare them as a group (one glazing type) and pick the best performing one.

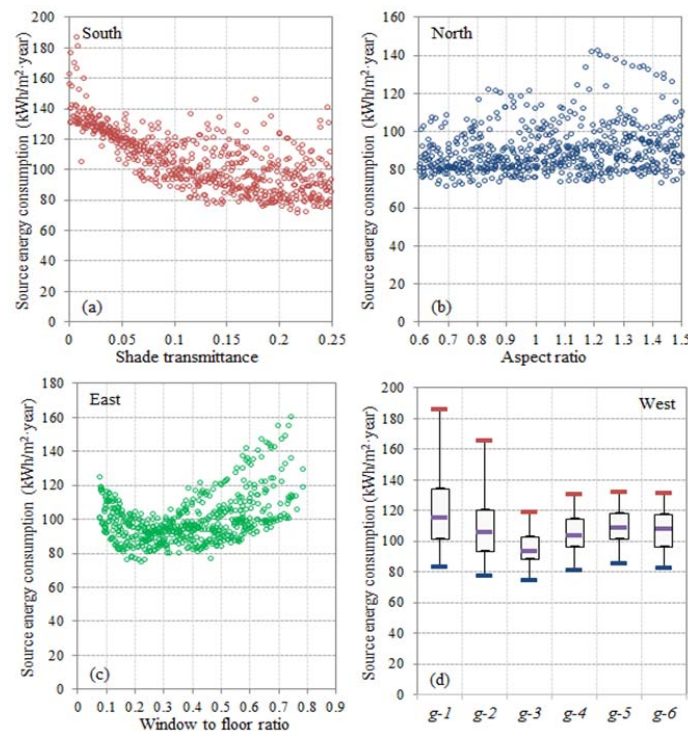


Figure 8. Variation of source energy consumption with (a) τ_{sh} for south; (b) space ar for north; (c) wfr ratio for east and (d) boxplot of source energy consumption with different glazing systems for west

5. CONCLUSION

This paper presents a sensitivity analysis for five building performance metrics to seven selected design parameters. The purpose is to identify the more important factors with respect to a specific building performance so as to facilitate decision making in early building design stage and simplify further study such as optimization analysis. An integrated daylighting and energy model developed in a previous study with two improvements is employed to simulate the building performance. The studied building performances include UDI (500-2000 lux), lighting, heating and cooling demand and source energy consumption. Considering the possible influential factors, seven design parameters are selected. Glazing properties, such as visible transmittance, solar transmittance and U-value, are not continuously available from market and more importantly, they are not independent with each other, therefore they were grouped as one factor – glazing type- in the analysis. An uncertainty analysis was performed first to evaluate the necessity for further sensitivity analysis. The analysis is based on MC-LHS method with 140 runs. Significant dispersion of the building performance is evaluated, indicating that the studied factors should be carefully designed to achieve certain design targets. A sensitivity analysis was then performed: based on the characteristics of the building model, a variance-based method was selected. Using the extended FAST module in SimLab 2.2, a sample set with length of 460 data was generated and the first and total order sensitivity indices were computed for each studied design factor. The following conclusions are drawn from the results:

- For all evaluated building performances, window to floor ratio and glazing type show great impact;
- The impact of glazing type is usually involved with other design parameters;
- For different orientations, the rank of factor importance changes slightly because of different outside condition such as incident solar radiation and the resulting different shading schedule and lighting operation;

The value of sensitivity indices depends greatly on the range of inputs. When the range changes, both the indices value and importance rank may change. This paper focused on typical private office with only one external façade. The interior roller shade and lighting system were controlled with certain algorithms, so the results may not applicable to other space with different conditions.

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