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Impact of curtain wall configurations on building energy performance in the perimeter zone for a cold climate

T.C.Lam[a], Hua Ge[b,*], Paul Fazio[c]

[a]M.A.Sc student, Departmetn of Building, Civil and Enivronmental Engineering, Concordia University, Montreal, QC, CA, H3G 1M8
[b]Assistant Professor, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC, CA, H3G 1M8
[c]Late Professor, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC, CA, H3G 1M8

Abstract

The Analysis of Variances (ANOVA) approach is used to quantify the impact of nine curtain wall design parameters on the energy consumption of an office space in the perimeter zone of a typical office building in Montreal. The uncertainty analysis shows that the variation in curtain wall configurations has generally a greater impact on the cooling followed by heating, lighting and total energy consumption. The global sensitivity analysis shows that the window wall ratio is the most significant design parameter influencing the end-use energy consumption.

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Keywords: Curtain walls; Building envelope; Sensitivity analysis; Uncertainty analysis; Building simulations, Energy performance; ANOVA

1. Introduction

Curtain walls are commonly used in commercial buildings. Given the typically large glazing area used in curtain walls and the relatively low thermal performance of metal and glass, the energy consumption of buildings with curtain walls, especially in the perimeter zone, is more sensitive to the climatic conditions and the variation of façade design compared to buildings with opaque insulated façade [1]. The advancement of technologies in the thermal and optical properties of glazing helps improve the overall performance of curtain walls. Many high performance curtain wall systems can be achieved by integrating advanced glazing units, better insulated mullion and applying shading and

* Corresponding author. Tel.: +1-514-848-2424 ext. 8771; fax: +1-514-848-7965.
E-mail address: hua.ge@concordia.ca

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daylight control strategies [2-5]. These improvements can significantly reduce the energy consumption in space conditioning or lighting. However, the significance of curtain wall performance on the energy efficiency of buildings is also influenced by other design parameters such as the internal heat gain and occupancy profiles, etc. [6-7]. To achieve the desired energy efficiency in the perimeter zone of curtain wall buildings, it is important to take into account the interaction among façade design parameters, climatic conditions and building operation parameters.

The global sensitivity analysis can assist designers to identify the most influential parameters by taking into account the interdependency among design variables. This approach has been widely used in building designs. A detailed review of the application of sensitivity analysis in modeling building energy performance was summarized in [8]. Shen and Tzempelikos [9] applied the global sensitivity analysis on a study of the automated interior roller shades for an office building located in Philadelphia. The extended-FAST sensitivity analysis showed that window-to-floor ratio and glazing types had the most significant impact on the daylighting and energy performance. Mechri et al. [10] used the analysis of variance approach as an evaluation tool to conclude that the envelope transparent ratio is the most important parameter influencing the building energy performance.

The objectives of this paper is to quantify the significance of individual design parameters on the energy performance of the perimeter zone of office buildings with curtain wall façade by taking into account the interacting effect of façade design parameters, and to provide information that can help maximize the energy efficiency in the perimeter zone by optimizing the façade design at the conceptual design stage.

Nine façade design parameters are considered. They are glazing U-value (U_{gl}); solar heat gain coefficient (SHGC); visible transmittance (T_v); U-value of the spandrel panel (U_{sp}); U-value of frame (U_{fr}); window wall ratio (WWR); infiltration rate, and depth and inclination of overhang. A generic model representing a typical office unit in the perimeter zone of an office building located in Montreal is created in EnergyPlus. In total, 24,576 curtain wall configurations are sampled and simulated for four cardinal orientations. There are in total 98,304 simulations performed. All simulations have the same settings for HVAC and lighting systems, plug loads, occupancy and operation profiles. The influence of façade design parameters on the annual heating, cooling, lighting, and total energy consumption is quantified through uncertainty and global sensitivity analyses. The coefficient of variation obtained from the uncertainty analysis indicates the sensitivity of the end-use energy consumption with respect to the variation of curtain wall configurations. The total sensitivity index obtained by variance-based global sensitivity analysis quantifies the total effect of each individual design parameter on the energy consumption by taking into account the interacting effect among the nine design parameters. The most significant design parameters are identified. The methodology, analysis procedure, results and conclusions are presented in the following sections.

2. Methodology

A hypothetical office unit representing a typical office space on the intermediate floor in the perimeter zone of an office building in Montreal is modeled in EnergyPlus. The exterior façade is completed with different curtain wall configurations. Simlab 2.2 , a program designed for Monte Carlo-based uncertainty and sensitivity analysis, is used for sampling. The uncertainty analysis is used to quantify the sensitivity of the end-use energy consumption in the perimeter zone to the variation of curtain wall configurations. The global sensitivity analysis is used to quantify and rank the significance of individual parameters on the end-use energy consumption. An open-source statistical computing program R [11] with a customized code is used to calculate the first order and total sensitivity index of individual design parameters.

2.1. Model setup in EnergyPlus

The hypothetical office unit is constructed for a single occupant according to common building practices for offices in North America [12]. One exterior façade is completed with curtain wall. The other three walls are regarded as internal partitions. An overhang is installed above the vision panel as the shading device. A highly energy efficient design is assumed for determining plug load and lighting power density. Continuous dimming (according to daylighting level) is activated when the illuminance is above the 500 lux set-point at the height of 0.8 m above the floor in the center of the office unit. The thermostat settings are 20ºC for heating and 25ºC for cooling during working hours of 08:00 to 18:00 with a night setback temperature of 13ºC in the winter and 30ºC in the summer, respectively.

The climate file used is WYEC2, created by WATSUN Simulation Laboratory. Table 1 lists the details of the building and system settings in the base case model. The range and distribution of the nine curtain walls design parameters are listed in Table 2.

Table 1 Design values set in the base case model.

Building information	Design value (SI units)
Dimension of office unit	4.0 m, 4.0 m and 3.6 m (D x W x H)
Heat gain from occupant	115W
Plug load	One desktop computer and printer (80 W)
Lighting power density	7.5W/m^2
Dimming control set-point	500 lux
HVAC Type	Package type heat pump Heating COP=2.75, Cooling COP=3.00
Operating hours	08:00-18:00 (weekdays), 09:00-13:00 (weekends)
HVAC setpoints	Heating 20ºC (set back temperature 13ºC) Cooling 25ºC (set-back temperature 30ºC)

Table 2 Range and distribution of the nine design parameters.

Design Variable	Symbol	Unit	Distribution	Range
Types of glazing		-		
i. U-value of glazing	U_{gl}	W/m^2 · K	PDF	1.10 to 2.50
ii. Solar heat gain coefficient	SHGC	-	PDF	0.33 to 0.70
iii. Visible transmittance	T_v	-	PDF	0.16 to 0.79
U-Value of frame	U_{fr}	W/m^2 · K	Uniform	0.80 to 8.80
U-Value of spandrel	U_{sp}	W/m^2 · K	Uniform	0.15 to 0.28
Window wall ratio	WWR	-	Uniform	0.10 to 0.90
Infiltration	Infil	L/m^2 · s	Uniform	0.01 to 0.22
Depth of overhang	D_h	-	Uniform	0.10 to 1.00
Inclination of overhang	Da	degree	Uniform	0.00 to 90.0

The three primary thermal and optical properties of glazing i.e. U-value, SHGC and T_v are included in the design variables. Constant values of U-value, SHGC and T_v are assumed in simulations. Given the fact that these three properties are interrelated, to generate samples that represent realistic products, the available glazing products certified by the National Fenestration Rating Council (NFRC) are analyzed. A database containing 2,858 glazing units for curtain walls from 40 manufacturers is created. The database representing the existing correlation among U-value, SHGC and T_v is input into Simlab and 24,576 new combinations of U-value, SHGC and T_v are generated using the Stein method. The Stein method in Simlab can generate new samples for inputs based on the existing correlated samples. The Probability Density Functions (PDF) of U-value, SHGC, and T_v from the generated samples are compared with the PDF of these properties from the actual products. The distribution of the sampled data is in good agreements with the manufacturer's data.

2.2. Uncertainty analysis

The uncertainty is quantified by the coefficient of variation (ν), which is the ratio of the standard deviation (σ) to the mean value (μ). The coefficient of variation (ν) indicates the dispersion of the outputs. The smaller the coefficient of variation, the less sensitive the end-use energy consumption to the variation of curtain wall configurations.

2.3. Sensitivity analysis

The sensitivity analysis provides insights on parameters that contribute to the variation of outputs and determines the most significant parameters so that the greatest benefits can be obtained from improving the most significant parameters contributing to the largest variation of outputs [13]. The global sensitivity analysis, which can evaluate the importance of a parameter throughout the entire multivariate space of a model, is used in this paper.

The variance-based approach is the analysis of variance, known as ANOVA, such as Sobol', First Amplitude Sensitivity Test (FAST) [13] and extended-FAST. The ANOVA is to apportion the variance of an output to the input variables. The advantages of ANOVA are its ability to provide quantitative insights of both the independent influence of each individual design parameter and the interacting effect among those individual design parameters. Therefore, the significance of individual design parameters can be quantified and prioritized. Sobol' method is used in this paper for the global sensitivity analysis because the sampling based on Sobol' sequences is found to produce the most robust results when dealing with building simulations [14].

3. Results and discussion

3.1. Uncertainty analysis

Figure 1 shows the box plot and coefficient of variation of the heating, cooling, lighting and total energy consumption of this office unit for each cardinal orientation. In general, the coefficient of variations is similar for all four orientations for heating, lighting, and total energy consumption, which is about 34-38%, 28%, and 17-20%, respectively. For the cooling energy consumption, the dispersion is about 55% for the east and west façades, 65% for the south facade, and 42% for the north facade. These results indicate that the variation of curtain wall configurations has generally the greatest impact on the cooling followed by heating, lighting and total energy consumption. The variation of curtain wall configurations has much less impact on the cooling energy consumption for the north façade than facades for other three orientations. The design of curtain walls has a greater impact on the heating and cooling energy consumption for the south façade.

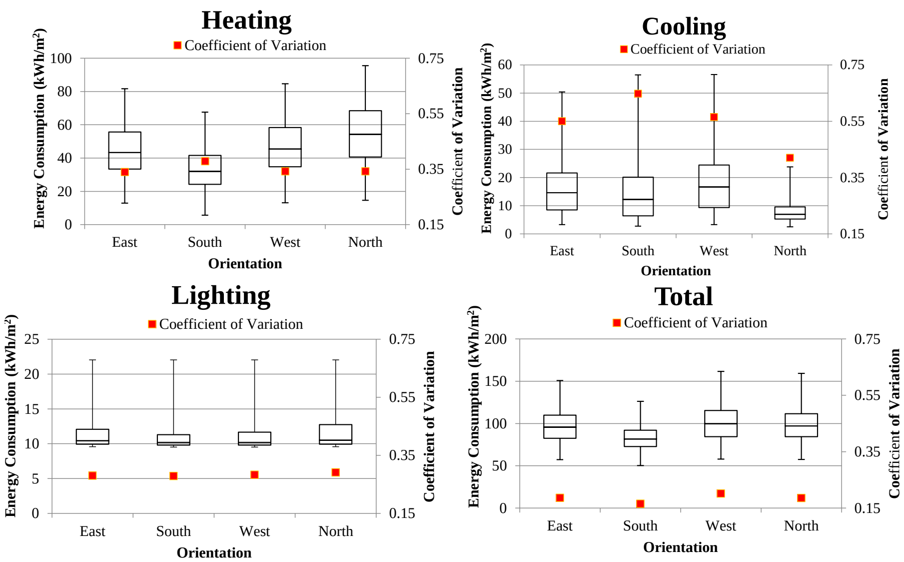

Figure 1 Box plot of end-use energy consumption showing the maximum, upper quartile, median, lower quartile and the minimum values, and coefficient of variation.

3.2. Global sensitivity analysis

The total sensitivity index is used to quantify the influence of design parameters. As shown in Table 3, the window wall ratio (WWR), U-value of glazing (U_{gl}) and infiltration rate are the three most significant parameters influencing the annual heating energy consumption in the perimeter zone of the hypothetical office building for all four orientations. The WWR has the most significant impact with a total sensitivity index of about 0.6-0.8, which is about 1.1 to 1.9 times higher than the second most significant parameter, i.e. U-value of glazing. The second and the third most significant parameters have similar total sensitivity indices. Design parameters such as SHGC, the overhang inclination and depth, U-value of frame and visible transmittance have comparable effect on the annual heating energy consumption for all four orientations. The influence of U-value of spandrel panel is the least for all four orientations.

The WWR, SHGC and depth of overhang (Depth) are the three most significant parameters influencing the annual cooling energy consumption for east, south and west facing facades, while for the north façade the WWR SHGC, and U_{gl} are the three most significant parameters. The WWR has the most significant impact with a total sensitivity index of about 0.6-0.8, which is about 2.8-4.0 times higher than the second most significant parameter, i.e. SHGC on the east, south and west orientation. For the north façade, the total sensitivity index of WWR is about 0.6, which is 1.5 times higher than SHGC.

Table 3 Ranking of the 9 input parameters for end-use energy consumption.

Rank	East		South		West		North	
				Heating				
1	WWR	0.69	WWR	0.63	WWR	0.71	WWR	0.79
2	Ugl	0.52	Ugl	0.55	Ugl	0.50	Ugl	0.41
3	Infiltration	0.25	Infiltration	0.32	Infiltration	0.23	Infiltration	0.19
4	SHGC	0.19	SHGC	0.29	SHGC	0.18	SHGC	0.14
5	Depth	0.15	Depth	0.26	Depth	0.14	Ufr	0.11
6	Inclination	0.14	Inclination	0.20	Inclination	0.14	Inclination	0.11
7	Ufr	0.14	Ufr	0.19	Ufr	0.13	Depth	0.11
8	Tv	0.14	Tv	0.18	Tv	0.13	Tv	0.11
9	Usp	0.12	Usp	0.16	Usp	0.11	Usp	0.09
				Cooling				
1	WWR	0.75	WWR	0.70	WWR	0.76	WWR	0.60
2	SHGC	0.19	SHGC	0.25	SHGC	0.19	SHGC	0.39
3	Depth	0.06	Depth	0.08	Depth	0.06	Ugl	0.06
4	Ugl	0.03	Ugl	0.04	Ugl	0.02	Depth	0.03
5	Inclination	$7x10^{-3}$	Tv	0.01	Tv	$6x10^{-3}$	Tv	0.02
6	Tv	$4x10^{-3}$	Infiltration	$5x10^{-3}$	Inclination	$6x10^{-3}$	Infiltration	$7x10^{-3}$
7	Infiltration	$2x10^{-3}$	Inclination	$2x10^{-3}$	Infiltration	$1x10^{-3}$	Usp	$7x10^{-3}$
8	Usp	$2x10^{-3}$	Usp	$2x10^{-3}$	Usp	$1x10^{-3}$	Inclination	$6x10^{-3}$
9	Ufr	$2x10^{-4}$	Ufr	$3x10^{-4}$	Ufr	$1x10^{-4}$	Ufr	$2x10^{-3}$
				Lighting				
1	WWR	0.88	WWR	0.90	WWR	0.89	WWR	0.86
2	Depth	0.19	Depth	0.23	Depth	0.20	Depth	0.16
3	Inclination	0.09	Inclination	0.11	Inclination	0.10	Tv	0.10
4	Tv	0.08	Tv	0.06	Tv	0.07	Inclination	0.08
5	Ugl	$2x10^{-3}$	SHGC	$6x10^{-4}$	Ugl	$1x10^{-4}$	SHGC	$9x10^{-4}$
6	SHGC	$1x10^{-4}$	Ugl	$7x10^{-5}$	SHGC	$6x10^{-6}$	Ugl	$4x10^{-4}$
				Heating + Cooling+ Lighting Energy consumption				
1	WWR	0.96	WWR	0.93	WWR	0.95	WWR	0.90
2	Ugl	0.31	Ugl	0.43	Ugl	0.28	Ugl	0.40
3	Infiltration	0.17	Infiltration	0.25	Infiltration	0.15	Infiltration	0.20
4	Inclination	0.11	Depth	0.22	Inclination	0.09	SHGC	0.12
5	Depth	0.11	Inclination	0.19	Depth	0.09	Inclination	0.12
6	Ufr	0.10	SHGC	0.18	SHGC	0.09	Depth	0.12
7	Tv	0.10	Ufr	0.16	Ufr	0.09	Ufr	0.12
8	SHGC	0.10	Tv	0.16	Tv	0.09	Tv	0.11
9	Usp	0.08	Usp	0.13	Usp	0.07	Usp	0.09

The WWR, depth and inclination of overhang (Inclination) are the three most significant parameters influencing the annual lighting energy consumption for east, south and west facades. The WWR has the most significant impact with a total sensitivity index of about 0.9, which is about 3.9-4.6 times higher than the second most significant parameter, i.e. depth of overhang. The second and the third most significant parameters i.e. overhang depth and inclination, have similar total sensitivity indices. For the north façade, the total sensitivity index of the WWR is 5.4 times higher than the second most significant parameter, depth of overhang.

As for the sum of heating, cooling and lighting energy consumption, given that Montreal is in a heating-dominated climate, similar to the annual heating energy consumption, the WWR, U_{gl}, and infiltration are the three most significant influencing design parameters.

4. Conclusion

The influence of nine curtain wall design parameters on the energy performance of a hypothetical office unit representing a typical office space in the perimeter zone is evaluated using a variance-based approach (ANOVA). The uncertainty analysis shows that the variation of curtain wall configurations has generally the greatest impact on the cooling followed by heating, lighting, and total energy consumption. The variation of curtain wall configurations has much less impact on the cooling energy consumption for the north façade than the other three orientations with the greatest impact on the south façade.

The global sensitivity analysis shows that the WWR is the most significant design parameter influencing the heating, cooling, lighting and total energy consumption for the office unit in the perimeter zone. Typically the total sensitivity index of WWR is 3.9-5.4 times higher than the second significant parameter for the energy consumption.

The same methodology can be applied to other climates and the energy performance data generated in this research could be further analyzed to provide general design recommendations, which could served as a general guideline for facade design without having to evaluate every design case by case.

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