Study of different glazing modelling approaches in assessing energy performance of curtain wall systems using EnergyPlus

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Abstract

Six glazing modelling approaches are available in EnergyPlus, including the Full Spectral Method, the Average Spectral Method, the WINDOW Report Method, the Bi-directional Scattering Distribution Functions Method, the Refraction Extinction Method, and the Simple Window Model. A simplified approach provides predictions with assumptions which affect the quality of prediction. The trade-off between the ease of operation for users and the fidelity of model poses the difficulty in selecting the appropriate approaches. This paper suggests selecting an appropriate approach based on three criteria: computational cost, ability to reproduce consistent results and uncertainty.

A base model of the perimeter zone in a typical office building in Montreal is created in EnergyPlus. The variation of energy consumption due to varying fifteen glazing units is predicted using six glazing modelling approaches. The uncertainty of the six modelling approaches is quantified. The advantages and limitations of each modelling approach are discussed.

1 Introduction

The building envelope plays an important role in the energy efficiency of buildings (Sadineni et al. 2011). A significant energy saving can be archived by improving the overall thermal performance of curtain walls (Ge & Fazio 2004). In recent years significant advancements in fenestration technologies have been made (Jelle et al. 2012). The pre-evaluation of building envelope designs with the help of simulation programs can facilitate identifying more energy efficient options. However, all simulation programs are subjected to uncertainties (Macdonald 2002). For example, uncertainties in physical parameters such as the inconsistency of building material properties and workmanship, uncertainties in scenario parameters such as the variations of outdoor climate and occupancy, and uncertainties originated from the deviations between design and construction are all sources of uncertainties in building simulations. The inclusion of uncertainty analyses of the simulations can improve the reliability of designs (Hopfe & Hensen 2011).

Buildings with curtain walls are subjected to larger variations in building energy consumption than those buildings with a higher portion of opaque façade because the glazed portion of curtain walls is more responsive to changing outdoor environments (Poirazis et al. 2008). Previous studies showed that annual energy savings by a fenestration depends on window type, its orientation, climatic conditions, buildings dimensions and thermal transmittance of buildings' walls and roof (Singh & Garg 2009). They all concluded that the uncertainty in predicting the energy performance of buildings by simulation programs cannot be neglected, which can be a major factor in decision-making (Hopfe et al. 2013).

EnergyPlus is a building energy performance simulation program. It provides six approaches to model glazing portion in fenestration, including the Full Spectral Method (FSM), the Average Spectral Method (ASM), the WINDOW 5 Report Method (WRM), the Bi-directional Scattering Distribution Functions Method (BSDF), the Refraction Extinction Method (REM), and the Simple Window Model (SWM)(EnergyPlus 2013). The six approaches allow different ways to specify the glazing properties but present different restrictions on certain configurations of glazing units. The six approaches differ in terms of level of detail and applicability. Detailed models require a considerable amount of detailed information as the input parameters. Increasing the level of detail increases the difficulty in performing the simulations. Decreasing the level of details degrades the model fidelity, which may lead to greater uncertainty in the modelling results.

An appropriate modelling approach should be able to reproduce predictions which fit with the experimental data (Van Buren et al. 2014); however, this norm tends to steer the approach selection towards the detailed approach which fits better with the experimental data. The approach selection strategy loses ground when the experimental data is not available in early design phase.

To our knowledge, only one previous study by (Peter et al. 2010) compared the discrepancies in the predicted energy consumption by using different glazing modeling approaches. They concluded that the energy consumption predicted using the SWM agreed well with the results from the FSM, which is the only recommended model in EnergyPlus (EnergyPlus 2013). Due to lack of literature support, users typically choose the glazing modeling approach based on subjective judgement or the availability of input parameters.

The purpose of this paper is to compare the results obtained by the six glazing modelling approaches available in EnergyPlus and provide some recommendations when selecting glazing modelling approaches on the basis of computational time, the ability to reproduce consistent results, and uncertainty. The strength and limitation of each approach is also summarised.

2 Description of the six glazing modelling approaches

Spectral data, and the optical and thermal properties of glazing used in the following modelling approaches can be obtained from

- Manufacturers' measured data;
- Optical Data Library maintained by the Windows Group at Lawrence Berkeley National Laboratory(Optics 6.0 2013);
- Outputs from WINDOW program including spectral data, optical and thermal properties(Robin et al. 2008).

Full Spectral Method (FSM)

The FSM requires the wavelength-by-wavelength spectral data (transmittance, front reflectance, and back reflectance) covering the solar spectrum from about 0.25 to 2.5 microns as inputs. The wavelength values are in ascending order and the transmittance and reflectance values are at normal incidence angle.

EnergyPlus calculates transmittance and absorptance for different incident angles based on the weather file for each wavelength. Solar transmittance and absorptance are weighted by a standard solar spectrum, and visible transmittance is weighted by the response of the human eye for different incident angles. This approach is recommended if data is available.

Average Spectral Method (ASM)

The ASM requires the inputs of transmittance, front and back reflectance of solar spectrum and visible light, infrared transmittance, front and back emissivity and conductivity of each layer of glazing. The determination for solar transmittance and reflectance are averaged over the solar spectrum, and the values for visible transmittance and reflectance are weighted average over the solar spectrum according to the response of the human eye.

The average values of optical properties are determined at normal incidence, which can be obtained from the WINDOW program or from manufacturer's data. If the values of optical properties are obtained from the WINDOW program, the results predicted by the ASM will be close to the results predicted by the WRM with a slight difference resulting from rounded up errors. However, when the average values of optical properties are determined by using the manufacturer's data, the results predicted by the ASM can deviated from the results predicted by WRM. The data excerpted from the WINDOW program and then inputted into EnergyPlus is automatically rounded up to six decimal places for the Average Spectral Method (ASM), while the values output from the WINDOW report imported to EnergyPlus are rounded up to three decimal places for the WINDOW Report Method (WRM).

WINDOW Report Method (WRM)

The WINDOW program is used to generate the WINDOW report for EnergyPlus. The WINDOW report includes the U-value, the SHGC, the calculated values of optical properties such as the transmittance, the absorptance, the front and back reflectance for the glazing unit at different incidence angles. The report also lists the average values of thermal properties and optical properties over the solar spectrum and visible spectrum of individual layers including glazing, gas gap or films at different incidence angles. When WRM is used for simulating glazing units in EnergyPlus, the path of the WINDOW report is specified in EnergyPlus, such that, EnergyPlus can read the optical properties of the glazing units in the WINDOW report. EnergyPlus takes the average values of optical properties of individual layers of the glazing units at normal incidence in the WINDOW report.

Bi-directional Scattering Distribution Functions Method (BSDF)

The BSDF is an alternative way to calculate the optical properties of glazing, especially for the complex fenestration systems that include the shading devices or fenestration attachments. BSDF, which consists of Bi-directional Reflectance Distribution Function or BRDF and Bi-directional Transmittance Distribution Function or BTDF, describes how light coming from a certain direction is transmitted and reflected in other directions. These directions are obtained by discretizing a hemisphere into 145 patches in the Klems basis (Robin et al. 2008). This process results in a matrix of 145 incoming by 145 outgoing directions.

Refraction Extinction Method (REM)

The index of refraction and extinction coefficient are used to specify glazing properties. This approach is limited to the glazing in which the front and back optical properties of the glass are the same. Hence, this approach cannot be applied to model coated glazing. The extinction coefficients for glass types vary approximately from $4 m^{-1}$ for water-white glass to $32 m^{-1}$ for high iron oxide content (greenish cast of edge) glass (Duffie & Beckman 2013). The extinction coefficient for low-iron glass, which is the default outer cover material, is $15 m^{-1}$ (EnergyPlus 2013).

Simple Window Model (SWM)

In the SWM, simplified window performance indices including U-value of glazing (U_{gl}), solar heat gain coefficient (SHGC), and the optional input, visible transmittance (VT), are used to specify the glazing properties. This approach converts the simple indices into an equivalent single layer window. Approximate angular properties of the specified fenestration are determined and the optical properties for individual layers of glazing units are generated. Then EnergyPlus uses the generated layer-by-layer properties to model the glazing units (Arasteh 2010). The input required by the SWM can be either for glazing-only windows (with no frame) or for an average performance of window including the frame. The model produces an equivalent window glazing layer with no frame. (EnergyPlus 2013).

3 Methodology

To compare the six different glazing modelling approaches, a base energy model is built in EnergyPlus. Fifteen glazing units, including single, double, triple and quadruple glazing units with clear and bronze colour, are selected as variables to be inputted to the base energy model. Routine simulations are repeated for all fifteen glazing units for each modelling approach. The annual heating, cooling, lighting, and total energy consumption for the fifteen glazing units by each modelling approach is analyzed. The mean and standard deviation of simulated results of fifteen glazing units are calculated. Due to the difference in input parameters and the computation algorithms of each modelling approach, these six approaches provide similar but different results. By evaluating the mean and standard deviation of fifteen glazing units for six modelling approaches, the coefficient of variation in heating, cooling, lighting and total energy consumption is compared among the six modelling approaches. The coefficient of variation reflects the uncertainty of the modelling approaches.

Glazing units

Table 1 lists the fifteen glazing units selected for this study. Since the SWM and the REM cannot be applied to model glazing with coatings, there is no coated glazing in the fifteen glazing units selected for all modelling approaches.

Table 1: Fifteen glazing units selected

Glazing units ID	Glazing unit description	U-factor[1], center-of glass ($W/m^2.K$)	SHGC[1]	Visible transmittance[1] (VT)
1	Single clear	5.913	0.861	0.899
2	Double bronze, 95% Argon	2.574	0.590	0.465
3	Double clear, 95% Argon	2.576	0.764	0.814
4	Double bronze, 95% Krypton	2.531	0.591	0.495
5	Double clear, 95% Krypton	2.532	0.764	0.814
6	Triple bronze, 95% Argon	1.635	0.488	0.319
7	Triple clear, 95% Argon	1.635	0.686	0.742
8	Triple bronze, 95% Krypton	1.572	0.488	0.319
9	Triple clear, 95% Krypton	1.573	0.686	0.742
10	Quadruple bronze, 95% Argon	1.202	0.411	0.219
11	Quadruple clear, 95% Argon	1.203	0.621	0.678
12	Quadruple bronze, 95% Krypton	1.131	0.412	0.219
13	Quadruple clear, 95% Krypton	1.132	0.621	0.678
14	Quadruple bronze, Xenon	1.110	0.412	0.219
15	Quadruple clear, Xenon	1.110	0.622	0.678

[1] The values of glazing properties are determined based on the environmental conditions NFRC 100-2010 (T_{in}=21ºC and T_{out}=-18ºC for U-value, T_{in}=24ºC and T_{out}=32ºC for SHGC, SHGC Solar=783W/m^2)

Base Energy Model in EnergyPlus

A hypothetical office unit representing a typical office space in the perimeter zone of a multi-storey office building in Montreal is built in EnergyPlus. The hypothetical office unit, which is 5m deep, 4m wide and 3.6m tall (floor to ceiling), is constructed for a single occupant according to common building practices for commercial offices. One exterior façade is completed with the curtain wall with glazing while the other three walls are regarded as internal walls. Adiabatic heat transfer (no heat loss) through the three internal walls, floor and ceiling is assumed. This set-up of the building model facilitates the comparison of energy consumption due to different curtain wall configurations. The internal load in the office room is assumed as highly energy efficient design which consists of heat generated by the single occupant (90 W)(ASHRAE 2010), electric equipment (80 W) and artificial lighting (LPD: 7.5 W/m^2)(ASHRAE 2011). Continuous dimming system (according to daylighting level) is activated when the illuminance is above the 500 lux setpoint located at the centre of the office unit at the height of 0.8 m above the floor. 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. The infiltration rate is assumed as 0.01 L/m^2.s. The climate file used is WYEC2, created by WATSUN Simulation Laboratory (Crawley 1998).

Uncertainty

To measure the robustness of each modelling approach, an uncertainty analysis is carried out. The uncertainty is quantified by the coefficient of variation (ν), which is the ratio of the standard deviation (σ) to the mean value (μ) given by Eqs. (1) and (2). The coefficient of variation (ν) indicates the dispersion of the outputs

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

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

$$\nu = \frac{\sigma}{\mu} \quad (3)$$

The smaller the coefficient of variation, the less the deviations of the predicted values from the mean values. Three possibilities lead to a model with the least uncertainty:

- The underlying assumptions are insensitive to the modelling approaches, or
- The required input parameters are insensitive to the modelling approaches, or
- Both of the underlying assumptions and the input parameters are insensitive to the modeling approaches.

4 Results and Discussion

Computational Cost

Table 2 lists the mean time used for simulating one glazing unit by each modelling approach. The simulation time is measured based on the simulation process running on a PC with Intel Core™ i3 @ 2.30GHz.

As shown in Table 2, the REM has the shortest mean simulation time of 1.42s. The mean simulation times by other modelling approaches exceed 10s and are similar. The longest mean simulation time is by the BSDF, which is 16.63s

Table 2: Mean time used for simulating one glazing unit

Approaches	Mean time (s)
Full Spectral Method (FSM)	11.77
Average Spectral Method (ASM)	12.69
WINDOW Report Method (WRM)	12.73
Bi-directional Scattering Distribution Functions Method (BSDF)	16.63
Refraction Extinction Method (REM)	1.42
Simple Window Model (SWM)	11.32

Ability to Reproduce Consistent Result with respect to FSM

Since FSM is the recommended modelling approach in EnergyPlus, the results obtained by other modelling approaches are compared with respect to FSM.

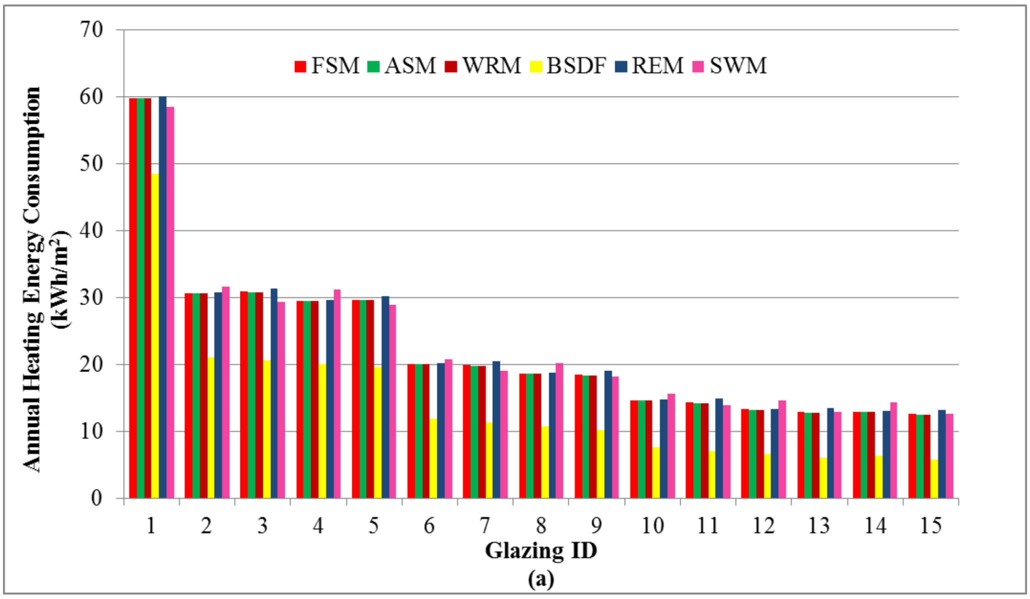

Figure 1: (a) Heating energy consumption predicted by six modelling approaches

Figure 1 shows the heating energy consumption (Figure 1a) and the statistic characteristics of the heating energy consumption (Figure 1b) predicted by the six modelling approaches. As shown in Figure 1a, the heating energy consumption obtained from the ASM and the WRM compares well with the prediction by the FSM. The BSDF predicts relatively lower heating energy consumption for all fifteen glazing units. The REM predicts higher heating energy consumption than the FSM does. The SWM predicts higher and lower heating energy consumption depending on the types of glazing units. As shown in Figure 1b, The FSM, the ASM, the WRM, the REM and the SWM predict similar heating energy consumption in terms of the median, maximum and minimum values; while the BSDF predicts lower median, maximum and minimum values.

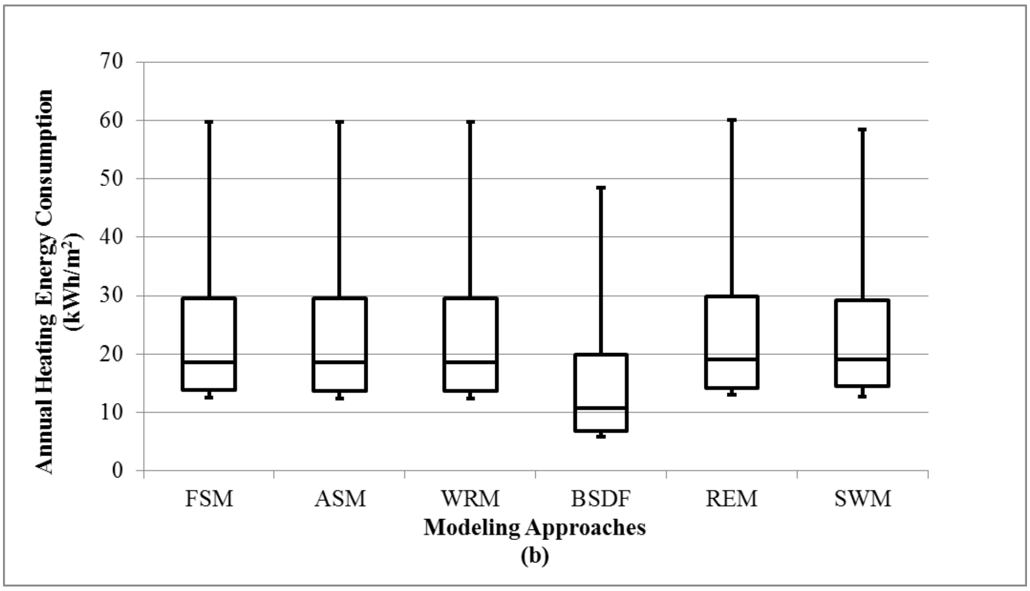

Figure 1: (b) Boxplot of the heating energy consumption showing the maximum, upper quartile, median, lower quartile and the minimum values for the six modelling approaches.

Figure 2 shows the cooling energy consumption (Figure 2a) and the statistic characteristics of the cooling energy consumption (Figure 2b) predicted by the six modelling approaches.

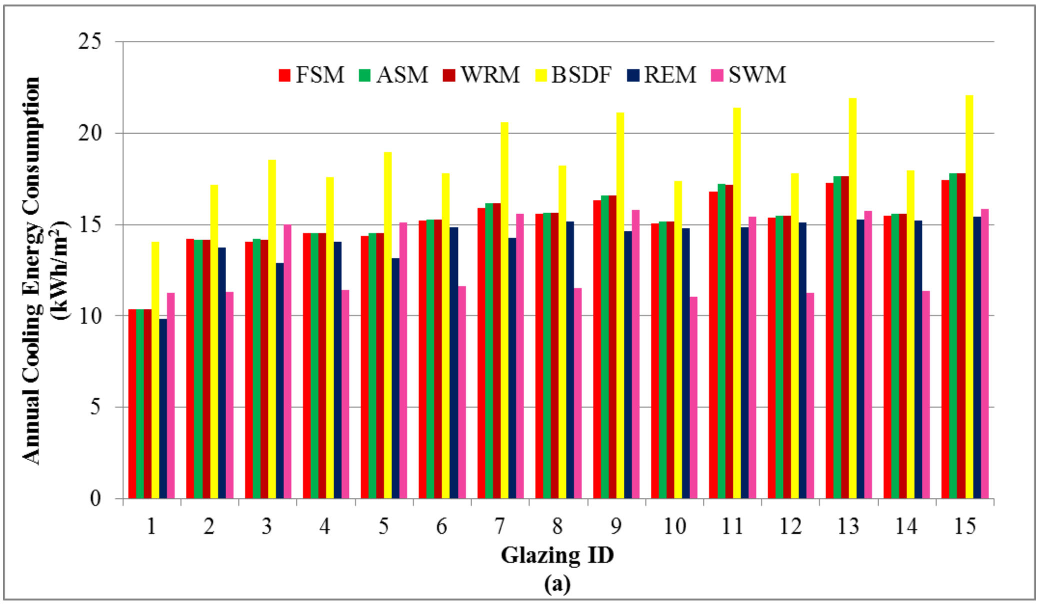

Figure 2: (a) Cooling energy consumption predicted by six modelling approaches

As shown in Figure 2a, the cooling energy consumption obtained from the ASM and the WRM compares closely with the prediction obtained from the FSM. The BSDF predicts relatively higher cooling energy consumption for all fifteen glazing units. The REM predicts lower cooling energy consumption than the FSM. The SWM predicts higher and lower cooling energy consumption depending on the types of glazing units. As shown in Figure 2b, the FSM, the ASM, and the WRM predicts similar cooling energy consumption based on the median, maximum and minimum values. The BSDF produces relatively higher median, maximum and minimum values. The REM produces relatively low median, maximum and minimum values. The SWM produces lower median and maximum values, but higher minimum values.

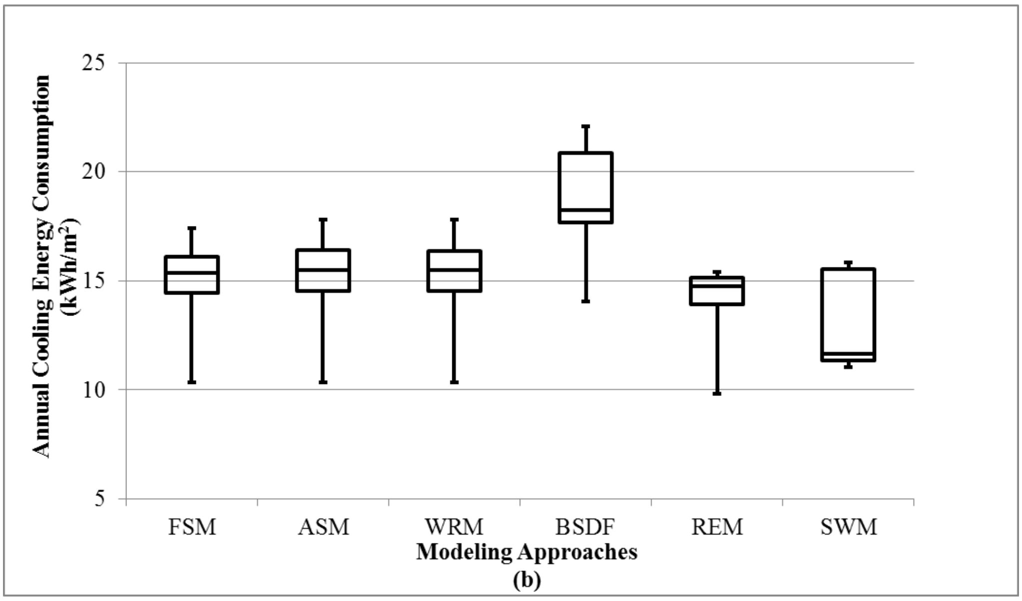

Figure 2: (b) Boxplot of the cooling energy consumption showing the maximum, upper quartile, median, lower quartile and the minimum values for the six modelling approaches.

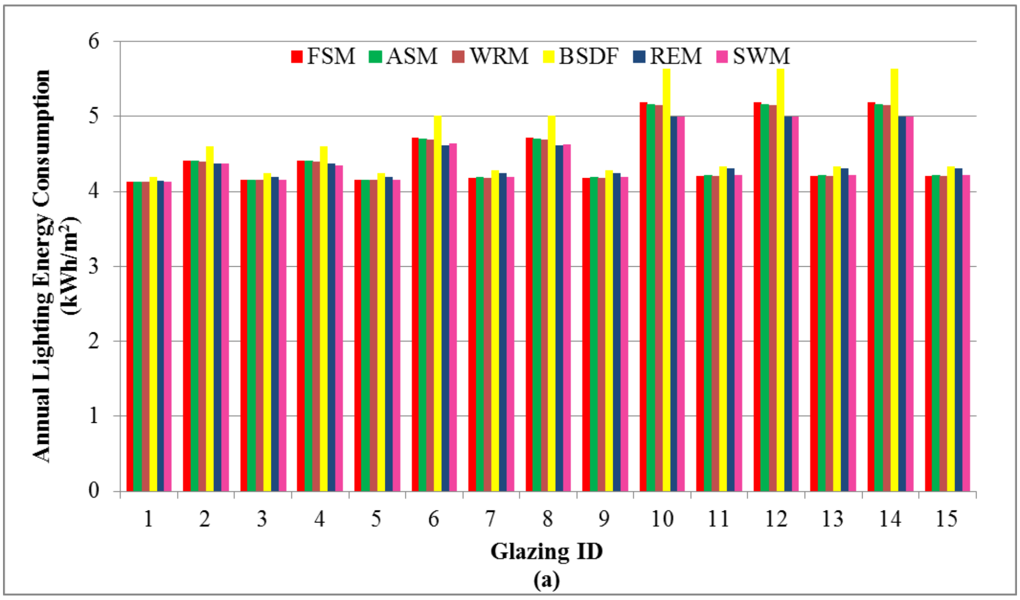

Figure 3: (a) Lighting energy consumption predicted by six modelling approaches

Figure 3 shows the lighting energy consumption (Figure 3a) and the statistic characteristics of the lighting energy consumption (Figure 3b) predicted by six modelling approaches. As shown in Figure 3a, the lighting energy consumption obtained from the ASM and the WRM matches well with the prediction by the FSM. The BSDF predicts relatively higher lighting energy consumption for all fifteen glazing units. The REM predicts higher and lower lighting energy consumption depending on the types of glazing units. The SWM predicts lower lighting energy consumption. As shown in Figure 3b, the FSM, ASM, and WRM predict similar lighting energy consumption in terms of the median, maximum and minimum values. The BSDF produces slightly higher median, maximum and minimum values. The REM produces relatively higher median and lower maximum values. The SWM produces lower median and maximum values.

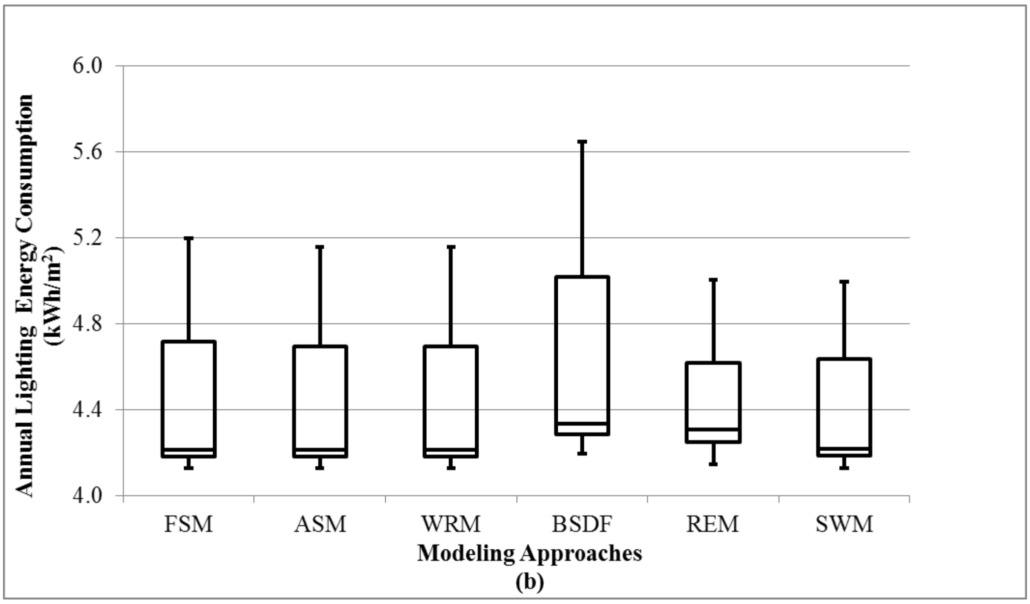

Figure 3: (b) Boxplot of the lighting energy consumption showing the maximum, upper quartile, median, lower quartile and the minimum values for six modelling approaches.

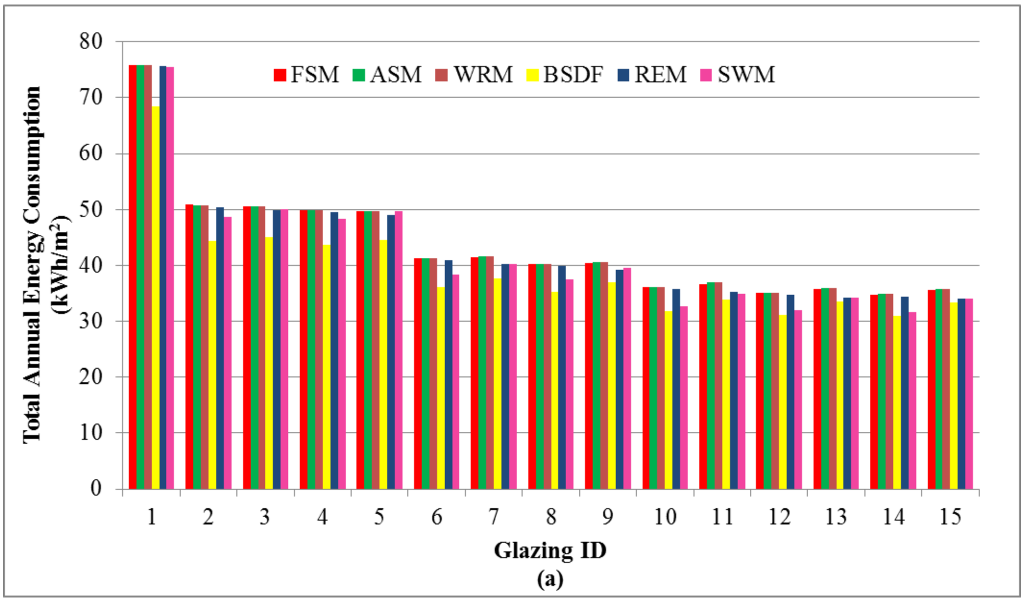

Figure 4: (a) Total energy consumption predicted by six modelling approaches

Figure 4 shows the total energy consumption (Figure 4a) and the statistic characteristics of the total energy consumption (Figure 4b) predicted by the six modelling approaches. The total energy consumption includes heating, cooling, lighting and fan energy consumption. As shown in Figure 4a, the total energy consumption obtained from the ASM and the WRM compares closely with the prediction obtained from the FSM. The REM, the SWM and the BSDF predict lower total energy consumption for all fifteen glazing units. As shown in Figure 4b, the FSM, the ASM, the WRM, and the REM predict similar total energy consumption in terms of the median, maximum and minimum values. The BSDF produces considerably lower median, maximum and minimum values. The SWM produces slightly lower median and minimum values.

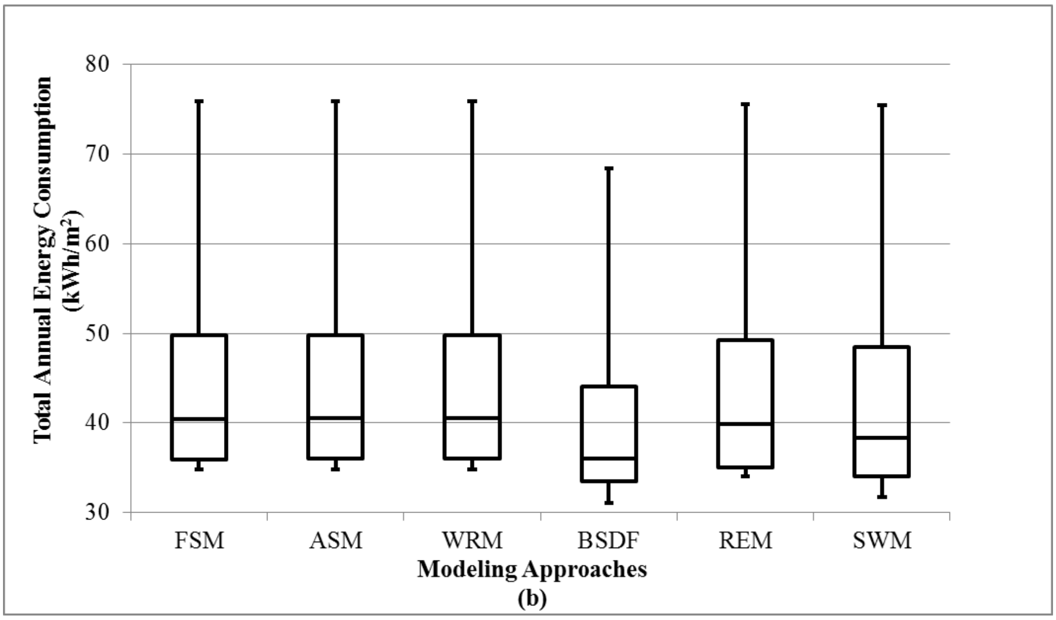

Figure 4: (b) Boxplot of the total energy consumption showing the maximum, upper quartile, median, lower quartile and the minimum values for the six modelling approaches

Uncertainty

As shown in Table 3, for all modelling approaches, the annual heating consumption has the largest coefficient of variation of 53% to 78%, followed by the total annual energy consumption of 24% to 27%, the annual cooling consumption of 10% to16%, and then the annual lighting consumption of 7% to12%.

The high value of the coefficient of variation implies large dispersions of the output data and larger uncertainty of the modelling approaches when predicting the heating energy consumption. The larger uncertainty is a result from the uncertainty of the input variables which may be due to the following:

- high sensitivity of one or group of input variables
- wider distribution of input variables
- high probability distribution in extreme values of input variables

As shown in Table 3, the BSDF has the largest coefficient of variation in predicting the heating energy consumption of up to 78% and the largest coefficient of variation in predicting the lighting energy consumption of up to 12%. This implies that the BSDF method is more sensitive to the variation of the input parameters when predicting the heating and lighting energy consumptions. This may be attributed to the fact that the main input parameters in BSDF are the bi-directional reflectance distribution function and bi-directional transmittance distribution function, which are highly sensitive to the incident angle. The distribution functions are 145 x 145 matrix for each incident angle. This is the only glazing modelling approach, which has the discretization for each incident angle.

The SWM has the largest coefficient of variation in predicting cooling energy consumption of up to 16% and the largest coefficient of variation in predicting total energy consumption of up to 27%. This may be attributed to the fact that EnergyPlus uses the inputs U-value and SHGC to determine the most probable composition of glazing units. For U-value ranges from 1.7 to 3.4W/m^2, SWM tends to yield the glazing units as reflective double glazing units (Arasteh 2010). Reflective double glazing units are able to reduce the cooling energy demand in the buildings.

Table 3: Mean, standard deviation and coefficient of variation of outputs

Approaches	Heating			Cooling			Lighting			Total		
	μ	σ	υ	μ	σ	υ	μ	σ	υ	μ	σ	υ
(FSM)	22.55	12.43	0.55	15.20	1.71	0.11	4.49	0.41	0.09	43.61	10.79	0.25
(ASM)	22.49	12.45	0.55	15.36	1.82	0.12	4.47	0.40	0.09	43.70	10.75	0.25
(WRM)	22.49	12.45	0.55	15.35	1.81	0.12	4.47	0.40	0.09	43.69	10.75	0.25
(BSDF)	14.26	11.06	0.78	18.85	2.20	0.12	4.70	0.56	0.12	39.12	9.54	0.24
(REM)	22.88	12.42	0.54	14.22	1.44	0.10	4.46	0.31	0.07	42.88	10.98	0.26
(SWM)	22.79	11.98	0.53	13.30	2.15	0.16	4.43	0.33	0.07	41.81	11.47	0.27

Strength and Limitation of the Six Modelling Approaches

The strength and limitation of six modelling approaches are listed in Table 4.

Table 4: Strength and limitation of six modelling approaches

Approaches	Strength	Limitation
Full Spectral Method (FSM)	• It is a high level of detailed simulation.	• It is not easy to obtain the wavelength to wavelength glazing properties unless the WINDOW program is run.
Average Spectral Method (ASM)	• Single value input can be obtained in manufacturer's data without running the WINDOW program.	
WINDOW Report Method (WRM)	• It is not necessary to re-input the window data. • It allows direct access to WINDOW's expanding database of over 1000 different glass types.	• This difference accounts for most of the variation in SHGC values reported by EnergyPlus and WINDOW. • This variation is more pronounced for window constructions of three glass layers or more.
Bi-directional Scattering Distribution Functions Method (BSDF)	• It is a high level of detailed simulation by input matrices.	• BSDF data obtained from WINDOW program takes longer to produce. • The simulation time is longer
Refraction Extinction Method (REM)	• It is the fastest simulation.	• It cannot be applied to model coated glazing. • Input variable can be seldom obtained from manufacturers, cannot be obtained from WINDOW program.
Simple Window Model (SWM)	• Simplest input variables which can be easily obtained.	• It is limited to specular glazing. • Many glazing units share the same U-value and SHGC but possess different angular properties; therefore, simulation by inputting simple index may not be modelling the expected glazing.

5 Conclusions

The paper compares the simulation results of fifteen glazing units using six different modelling approaches, available in EnergyPlus: the Full Spectral Method (FSM), the Average Spectral Method (ASM), the WINDOW Report Method (WRM), the Bi-directional Scattering Distribution Functions Method (BSDF), the Refraction Extinction Method (REM) and the Simple Window Model (SWM) in terms of computational time, ability of reproducing consistent result with respect to FSM, and uncertainty.

REM is the most efficient among the six modelling approaches. It takes about 2s while BSDF takes the longest mean simulating time of 16.63s. The mean simulating time of the rest of the modelling approaches are similar to one another (exceed 10s).

FSM is the only recommended approach by EnergyPlus when the full spectral data is available due to its high level of details required. A previous study concluded that the SWM is a better choice than the ASM. However, this paper indicates that the ASM and the WRM always provide the closest results to the FSM, although the inputs required in these two approaches are simpler. The BSDF predicts lower heating energy consumption, higher cooling energy consumption, higher lighting energy consumption, and lower total energy consumption for all fifteen glazing units. The REM predicts higher heating energy consumption, lower cooling energy consumption, higher and lower lighting energy consumption depending on the types of glazing units, and lower total energy consumption. The SWM predicts higher or lower energy consumption for space conditioning depending on the types of glazing, lower lighting energy consumption, and lower total energy consumption

For all modelling approaches, the annual heating consumption has the largest coefficient of variation. The BSDF has the largest coefficient of variation in predicting the heating and the lighting energy consumption. The SWM has the largest coefficient of variation in predicting cooling and the total energy consumption. The BSDF method is more sensitive to the variation of the input parameters when predicting the heating and lighting energy consumptions while the SWM is more sensitive to the variation of input parameters when predicting the cooling and the total energy consumptions.

Often the choice of the glazing modelling approaches is strongly affected by the availability of optical and thermal data. Users typically rely on the WINDOW program to access the full spectrum data, matrix of bi-directional reflectance distribution function or the bi-directional transmittance distribution function of the current commercial products, which are not easy to obtain from manufacturer’s catalogue. WINDOW program may not have the properties of some advanced glazing products, which makes it difficult to use FSM or BSDF methods. The ASM, REM and SWM methods allow users to model glazing in EnergyPlus when there is no detailed spectrum data available. This paper shows that the ASM is able to reproduce simulation results which are closer to that by FSM than both the REM and the SWM methods.

The REM method tends to overestimate the heating energy consumption but underestimate the cooling energy consumption with the underestimation of cooling energy consumption more significant. The SWM tends to overestimate and underestimate the cooling energy consumption and total energy consumption depending on the combinations of U-values and SHGC. For cooling dominated regions, or buildings with high internal gain, users should be caution about the cooling energy consumption results predicted by the REM and SWM methods. Given that only uncoated glazing units are investigated in this study, the conclusions are applicable only to uncoated glazing units. Future studies on coated and complex glazing units will be reported later.

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7 References

Arasteh, D., 2010. Modeling Windows in Energy Plus with Simple Performance Indices.

ASHRAE, 2011. *Advanced Energy Design Guide for Small to Medium Office Buildings*, American Society of Heating; Refrigerating and Air-Conditioning Engineers; The American Institute of Architects; Illuminating Engineering Society of North America; U.S. Green Building Council; U.S. Department of Energy.

ASHRAE, 2010. *ANSI/ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy*,

Model selection through robustness and fidelity criteria: Modeling the dynamics of the CX-100 wind turbine blade. *Mechanical Systems and Signal Processing*, 43(1-2), pp.246–259..

Crawley, D.B., 1998. Which Weather Data Should You Use for Energy Simulations of Commercial Buildings ? *Transactions-American Society Of Heating Refrigerating And Air Conditioning Engineers*, 104, pp.498–515.

Duffie, J.A. & Beckman, W.A., 2013. *Solar Engineering of Thermal Processes [Hardcover]* 4 edition., Wiley..

EnergyPlus, 2013. *Input Output Reference The Encyclopedic Reference to EnergyPlus Input and Output*, Ernest Orlando.

Ge, H. & Fazio, P., 2004. Experimental investigation of cold draft induced by two different types of glazing panels in metal curtain walls. *Building and Environment*, 39(2), pp.115–125..

Hopfe, C.J., Augenbroe, G.L.M. & Hensen, J.L.M., 2013. Multi-criteria decision making under uncertainty in building performance assessment. *Building and Environment*, 69, pp.81–90..

Hopfe, C.J. & Hensen, J.L.M., 2011. Uncertainty analysis in building performance simulation for design support. *Energy and Buildings*, 43(10), pp.2798–2805.

Jelle, B.P. et al., 2012. Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. *Solar Energy Materials and Solar Cells*, 96(7465), pp.1–28.

Macdonald, I.A., 2002. *Quantifying the Effects of Uncertainty in Building Simulation*. University of Strathclyde.

Optics 6.0, 2013. LBNL Windows & Daylighting Software. Available at: http://windows.lbl.gov/software/optics/6/o6_download.asp.

Peter, L., Justin, W. & Mahabir, B., 2010. A comparison of window modeling methods in EnergyPlus 4.0. In *Fourth National Conference of IBPSA-USA New*. New York City, New York: SimBuild 2010, pp. 177–184.

Poirazis, H., Blomsterberg, Å. & Wall, M., 2008. Energy simulations for glazed office buildings in Sweden. *Energy and Buildings*, 40(7), pp.1161–1170.

Robin, M. et al., 2008. *WINDOW 6.2 / THERM 6.2 Research Version User Manual*,

Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews*, 15(8), pp.3617–3631.

Singh, M.C. & Garg, S.N., 2009. Energy rating of different glazings for Indian climates. *Energy*, 34(11), pp.1986–1992.