A COMPARISON OF WINDOW MODELING METHODS IN ENERGYPLUS 4.0

Peter Lyons, PhD[1]; Justin Wong[2] and Mahabir Bhandari[3]
[1]Principal, Peter Lyons & Associates, Canberra, ACT, AUSTRALIA
peter.lyons@fenestralia.com
[2]Team Catalyst Proprietary Ltd, Maroubra, NSW, AUSTRALIA
justin@teamcatalyst.com.au
[3]Carli, Inc., Millers Falls, MA, USA
bhandari@designbuildersoftware.com

ABSTRACT

EnergyPlus Version 4.0 (U.S. Department of Energy, 2009) offers several powerful, alternative methods for defining windows and other fenestration systems in modeled buildings. Recently, a new 'Simple Window Model' was added to EnergyPlus. This tool allows the user to define a vertical window in an EnergyPlus building model using only the window's whole-system U-factor, solar heat gain coefficient and (optionally) its visible transmittance.

The Simple Window Model involves approximations which may lead to errors in some situations. This study presents a comparison and evaluation of several current, alternative methods for defining and modeling windows in EnergyPlus. We also briefly draw attention to the effect of using different weighting functions for the solar spectrum.

In a case study, a simple 10-storey, 5-zone per storey, office building was modeled. Results from three window-modeling methodologies are compared, conclusions are drawn and recommendations are presented.

INTRODUCTION: WINDOW MODELS IN ENERGYPLUS

Introduction

EnergyPlus is a powerful simulation tool for modeling heat flows in buildings. It is available free of charge and has an international development team. New versions of EnergyPlus are released twice a year. Its underlying algorithms and all supporting documentation are freely available and open to public review. The modeling capabilities for defining fenestration in EnergyPlus 4.0 are comprehensive and users can select from several different methods. Generally these methods include a full, layer-by-layer description of the optical properties of glazing layers and, in the case of insulating glass units, thermophysical properties of gas fills. Thermal data for window frames is included in imported window data files. EnergyPlus accepts data directly from the WINDOW 5 and THERM 5 simulation tools (Lawrence Berkeley National Laboratory, 2009). WINDOW 5 embodies the International Glazing Database which contains detailed optical data for several thousand international glass products. The dependence of optical properties (transmittance, reflectance and absorptance) on angle of incidence is accounted for in EnergyPlus algorithms.

Recently, a new 'Simple Window Model' was added to EnergyPlus. This tool allows the user to define a vertical window in an EnergyPlus building model using only the window's whole-system U-factor (thermal transmittance; U-value), SHGC (g-value) and (optionally) its visible transmittance (VT). This capability allows the user to specify windows in the not-uncommon scenario where full, detailed material and component (glazing, frame, spacer) data are not available. The Simple Window Model employs 'smart' algorithms which guess the most likely construction of the window and then synthesize a fictitious window having those specified, whole-system performance indices. Therefore the Simple Window Model involves approximations which may lead to errors in some situations.

This study presents a comparison and evaluation of current, alternative methods for defining and modeling windows in EnergyPlus. For a case study, a simple 10-storey office building with 5 zones per level was modeled in a wide range of Australian climates for a range of window and glazing combinations. Also examined was the impact on building annual energy of different window algorithms and spectral weighting functions. Results from all EnergyPlus window-modeling methodologies are compared, conclusions are drawn and recommendations are presented.

The objective of this study is to explore alternative ways to model windows in EnergyPlus and, if possible, infer limitations in current algorithms. EnergyPlus offers four ways to model vertical fenestration, in this paper hereafter referred to as "windows" (Winkelmann, 2001; Engineering Reference and Input-Output Reference, EnergyPlus v.4.0, 2009). Glass layer optical properties (spectral data) are derived from the International Glazing Database (IGDB) which is stored in the Optics 5 and WINDOW 5 computer programs.

There are four methods for inputting window constructions to EnergyPlus, three of which were reviewed in our study:

(1) Input full spectral data for each layer in the IDF – the *Full Spectral Model* ***(FSM);***
(2) Input averaged spectral data for each layer in the IDF – the *Spectral Average Model* ***(SAM)***;
(3) Import a WINDOW 5 EnergyPlus Report containing layer-by-layer calculated values and overall glazing system angular values – the *WINDOW 5 EnergyPlus Model* ***(W5M)***;
(4) Define a window using only the window's whole-system U-factor, SHGC and (optionally) its visible transmittance, VT. This method converts an arbitrary window configuration into an equivalent single layer – the *Simple Window Model* ***(SWM)***.

The first three of the above methods are, ideally, functionally equivalent, while the fourth involves approximations which are examined further in this paper. We did not review the *W5M* method in this paper.

Full Spectral Model

The FSM uses a layer-by-layer method where each glass layer is fully characterized in its spectral properties. Layers are defined individually in the EnergyPlus input data file (IDF), along with gas fills in the case of multiple glass layers. Frames, dividers and shading layers can be included. To use full spectral data in EnergyPlus, the data is included in the IDF using the object *WindowGlassSpectralData*.

Influence of weighting function
The impact of using the FSM further depends on the *shape* of its intrinsic solar spectral irradiance function. This can exert an additional and sometimes dramatic influence on calculated solar and visible properties of a glazing system. Optical calculations in EnergyPlus, for window layers input using full spectral data, use a spectral weighting data set that is derived from the Optics 5 data file, *ISO-9845GlobalNorm.std*. ISO 9845-1:1992 is based on two spectra, ASTM E891 Direct (the standard used by the U.S. National Fenestration Rating Council - NFRC) and ASTM E892 Global (the standard used in the European ISO/CEN system). An extensive discussion may be found in Gueymard and W.C. duPont (2009). In contrast to EnergyPlus, the modeling tool WINDOW 5 (the reference simulation software for NFRC) uses a different default spectral weighting data set, *W5_NFRC_2003.std* which is based on ASTM E891 Direct, only. The main issue with E891 and E892 are that they are now obsolete and have been withdrawn by ASTM. Gueymard and duPont strongly recommended that all existing spectra should be replaced by ASTM G173 (ASTM, 2003):

"*…This* [weighting set] *difference accounts for most of the variation in SHGC values reported by EnergyPlus and WINDOW 5 for full spectral data window layer input. This variation is more pronounced for window constructions of three glass layers or more. Users intending to select a window construction based on SHGC value for energy code compliance should base their selection on the value reported by WINDOW 5 since this is the officially recognized value.*"

As further discussed by Gueymard and duPont (2009): After any layer or bulk optical property p_λ has been determined at each appropriate wavelength λ, the corresponding 'broadband' (i.e. averaged) property, p, is obtained from the general equation

$$p = \frac{\int_{\lambda_0}^{\lambda_1} p_\lambda E_\lambda \Gamma_\lambda d\lambda}{\int_{\lambda_0}^{\lambda_1} E_\lambda \Gamma_\lambda d\lambda}$$

where λ_0 and λ_1 are the limits of integration (e.g. 300 and 2500 nm, respectively), E_λ is the source spectrum (i.e. the spectral irradiance incident on the glazing system), and Γ_λ is the detector's spectral response. For example for transmittance, the general property p_λ is replaced by T_λ. For visible transmittance *VT*, the detector curve Γ_λ is replaced by the photopic response curve of the human eye. This is a narrow, bell-shaped curve extending from approximately 400nm to 700nm with a peak in the green part of the visible spectrum at 550nm.

Figure 1 shows the impact on calculated U-factor and SHGC from using the W5 spectrum instead of the EnergyPlus spectrum. Note however that both methods use full spectral data from the IGDB.

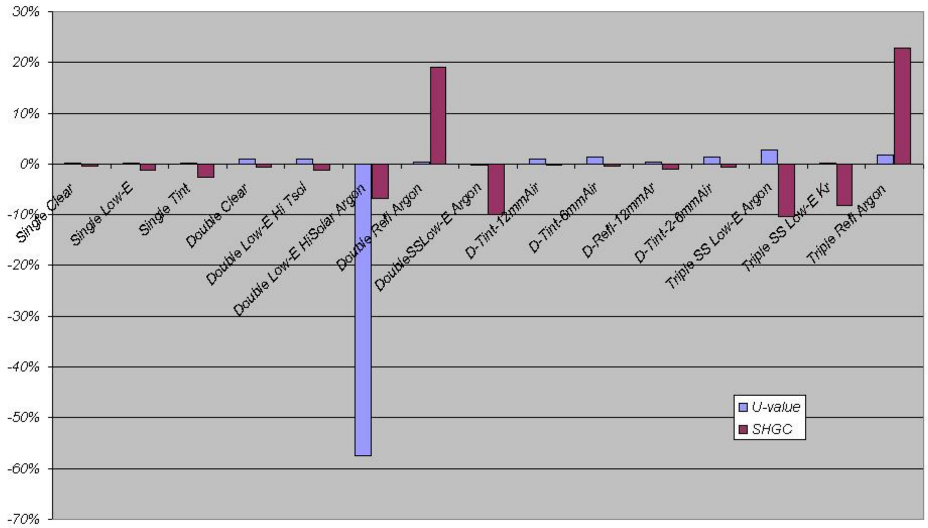


Figure 1. Impact on calculated U-factor and SHGC of using different spectral weighting functions: WINDOW 5 spectrum (W5_NFRC_2003) vs. EnergyPlus (ISO 9845) spectrum. Chart shows changes in U-factor and SHGC; e.g. Double Reflective argon has 19% larger SHGC when based on W5 spectrum compared with using EnergyPlus spectrum

Spectral Average Model

The SAM uses spectrally averaged optical properties for each layer of the glazing system. This is less accurate than the Full Spectral Model, because it averages optical properties of each layer before they are combined into a glazing system. Thus the wavelength-by-wavelength optical interactions between glass layers are lost from the calculation.

WINDOW 5 EnergyPlus Model

This method was not examined in our study but we outline its basis here for the sake of completeness.

The WINDOW 5 EnergyPlus Model *(W5M)* centers on the WINDOW 5 EnergyPlus Report (EPR) which is a text file that can be generated, exported by the WINDOW 5 program and read by EnergyPlus. It describes the material properties (thermophysical, optical and solar) of a complete, modeled window. One EPR is needed for each unique window. The EPR contains spectrally averaged (integrated) optical and solar properties for the complete glazing system including all layers as a composite system. For completeness, the file includes angular dependence for these properties but this angular information is not read by EnergyPlus. Instead, EnergyPlus applies angular dependence algorithms to normal-incidence, averaged optical properties so that a matrix of angular-dependent optical properties is recreated. This process inside EnergyPlus uses identical algorithms to those in WINDOW 5 (EnergyPlus Engineering Reference v4.0, 2009). Thus, the outcome is the same.

The EnergyPlus Report contains a reference to a *SpectralDataFile* but this is only an informative reference. There is no link between EnergyPlus and the original WINDOW 5 database that contains the spectral data.

Simple Window Model

Recently, a new 'Simple Window Model' (SWM) was added to EnergyPlus (Arasteh et al, 2009). This model was developed using regression equations based on performance indices calculated from full spectral data (from the IGDB) within WINDOW 5. Only single- and double-glazed systems were used to build the SWM (i.e. no triple-glazed systems or greater). As described above, the SWM allows the user to define a vertical window in an EnergyPlus building model using only the window's whole-system U-factor, SHGC and optionally, its visible transmittance (VT). The SWM allows the user to specify windows in the not-uncommon scenario where full, detailed material and component (glazing, frame, spacer) data are not available. The Simple Window Model employs 'smart' algorithms which guess the most likely construction of the window and then synthesize a fictitious window having those specified, whole-system performance indices. Therefore the SWM involves approximations which may lead to errors in representing the actual window. These potential errors are primarily related to the

(i) angular dependence of the glazing-system optical properties;
(ii) ratio of glass area to frame area;
(iii) approximation of multilayer glazing systems by a fictitious, single ('lumped') glazing layer, In particular, triple glazing was not considered during the SWM development;
(iv) use of the *W5_NFRC_2003.std* spectral weighting function which, as pointed out previously, uses only ASTM E891 direct solar data, without diffuse data.

WINDOW SYSTEMS MODELED

Glazing systems

For our EnergyPlus building modeling, 15 glazing systems were selected to span a wide range of U-factor and SHGC. They comprised clear, tinted and low-e technologies in various types of single, double and triple glazing. Figure 2 shows a scatter plot of SHGC vs. U-factor of the 15 glazing systems.

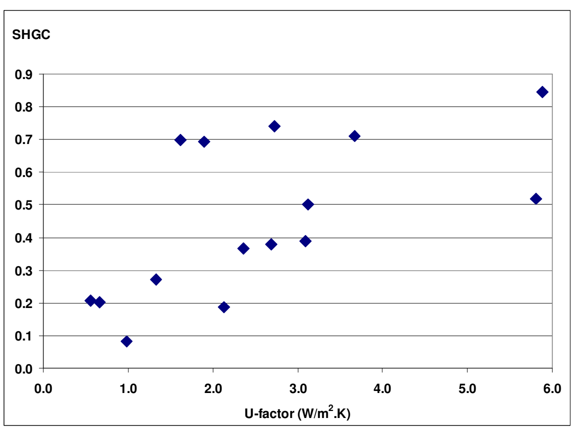


Figure 2. Fifteen glazing systems selected. Descriptions are given in Table 2.

Framing system

Aluminium framing with the following characteristics was assumed:

- Frame conductance (surface-to-surface, without air films): 23 W/m^2.K
- Edge-of-glass conductance equal to center-of-glass conductance
- Frame width (projected frame dimension): 40mm
- Total window area (per storey): 13.62 m^2
- Total vision area (per storey): 12.23 m^2
- Fraction of glass area (vision fraction): 0.898

ENERGYPLUS BUILDING MODEL AND CLIMATES

Envelope and climates

A 1200m^2, rectangular floor plate, 40m by 30m building was modeled. The floor-by-floor height was 3.6m and ceilings were 2.7m above floor level. These dimensions are considered typical for many commercial, tower-type office buildings in Australia. The floor plate was multiplied by 10 to ensure that reasonably large chilled-water loop loads were presented to the chiller which would then be sized at commercially available chilled-water plant components. Realistic HVAC systems were included in the modeling to make the results more relevant to buildings that EnergyPlus users typically model. External walls met the minimum insulation requirements required by the Building Code of Australia, Section J (ABCB 2009). Floors were modeled as typical concrete slab, and external walls were modeled as curtainwall spandrel systems.

Glazing systems used are shown in Table 2. Our simulations covered one subtropical, one Mediterranean and two cool-temperate climates as listed in Table 1. This ensured that our findings would not be skewed towards any particular climate. There are considerably hotter and colder climates in Australia (by a factor of more than two in both heating and cooling degree-days) but our study concentrated on four major cities with a combined population of 11 million people. A view of one level of the building is shown in Figure 3.

Table 1. Heating degree-days (HDD) and cooling degree-days (CDD) to base 18°C, for the four Australian climates used to model 1200m^2 floor plate commercial building (Thomas and Prasad, 1994).

Location	*HDD 18*	*CDD 18*
Brisbane (Queensland), BNE	232	1228
Sydney (New South Wales), SYD	743	556
Melbourne (Victoria), MEL	1423	244
Canberra (Australian Capital Territory), CBR	2160	241

Table 2. Fifteen glazing systems corresponding to Figure 2. T_{sol} denotes solar transmittance. Ar100% denotes 100% argon fill, etc.

Glazing system no.	Glazing system description	U-factor, center-of-glass (W/m^2.K) (NFRC 100-2004 conditions)	SHGC (g-value) (NFRC 100-2004 conditions)	Visible transmittance (VT)
1	Single clear	5.880	0.845	0.893
2	Single low-e	3.671	0.711	0.819
3	Single tinted	5.811	0.518	0.656
4	Double clear	2.730	0.741	0.803
5	Double low-e, hi-T_{sol}	1.896	0.694	0.738
6	Double low-e, hi-T_{sol}, Ar100%	1.617	0.698	0.738
7	Double reflective, Ar100%	2.133	0.188	0.162
8	Double spectrally selective low-e, Ar100%	1.325	0.272	0.637
9	Double tinted, 12mm air	2.688	0.379	0.294
10	Double tinted, 6mm air	3.094	0.389	0.294
11	Double reflective, 12mm Ar100%	2.364	0.367	0.364
12	Double tinted #2, 6mm air	3.124	0.500	0.445
13	Triple spectrally selective low-e, Ar100%	0.668	0.202	0.410
14	Triple spectrally selective low-e, Kr100%	0.563	0.207	0.456
15	Triple reflective, Ar100%	0.983	0.083	0.030

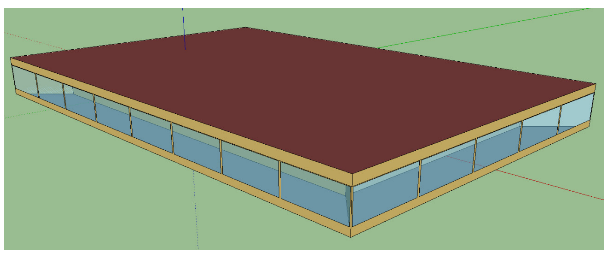


Figure 3. View of one level of 1200m^2 floor plate building.

The vision area to wall ratio of the modeled building was 76%.

Heating, Ventilating and Air-Conditioning (HVAC) System

A central cooling and heating plant was used, with ‘face zone VAV’ configuration representing typical HVAC systems for buildings of these types in Australia. The zone-side VAV turndown ratios were set to a standard practice (not so efficient) 50%. Damper action was set to normal, rather than reverse action.

The water side of the HVAC system was represented as having two equal-sized chillers with a nominal coefficient of performance of 4.5. Chilled-water reticulation was via a primary constant-speed loop. The chilled-water loop was designed to a standard 6^{o}C leaving and 12^{o}C entering, and design supply air temperature was also set to a standard 13^{o}C. These chillers were modelled to be served by a single cooling tower. As such, the configuration represents typical, run-of-the-mill design for this type of commercial office building.

RESULTS AND DISCUSSION

Introduction

The 15 framed glazing systems in Table 2 were simulated in the above EnergyPlus building model.

Full Spectral Model: Effect of Different Spectra

As discussed above, the most comprehensive glazing model in EnergyPlus model is the *Full Spectral Model* because it accounts for wavelength-dependent interaction between all layers in a glazing system. However, results depend on which spectrum is used to derive the overall solar transmittance of the glazing system. Consequently an effect might be expected mainly with SHGC, with a much smaller impact on U-factor.

Comparison of Full Spectral, Spectral Average and Simple Window Models

For the 5-zone building, the two groups of Figures 4 – 7 and 8 – 11 show normalized annual heating and cooling loads, respectively, for the four climates listed in Table 1. Three-letter IATA airport codes denote each city. For each glazing system, the vertical scales have been normalized with respect to the Full Spectral Model. This facilitates comparison between climates.

EnergyPlus IWEC files were used for all locations. Glazing systems are presented in the same order as in Figure 1. Each chart shows comparison results for the Full Spectral Model (underpinned by the EnergyPlus/ISO 9845 spectrum), the Spectral Average Model and the Simple Window Model. Note that the second and third models are based on that spectrum also. In version 4.0 of EnergyPlus, it was not possible to change the spectral weighting function used inside the program.

DISCUSSION AND ANALYSIS

Influence of spectral weighting function

In any whole-building modeling software, it is very important to have correct values for optical properties at glazing normal incidence, because properties at other angles of incidence are in turn based on normal-incidence information, which are modified by a factor calculated from an assumed angular-dependence curve.

When examining the different, full-spectrum models in EnergyPlus, both analyses used the same glazing spectral data files from the IGDB. In this way, any difference in results attributable to the spectral weighting function should become apparent.

Figure 1 shows the impact of using the WINDOW 5 spectrum *(W5_NFRC_2003)* vs. the EnergyPlus (ISO 9845) spectrum. The variation in SHGC is large and unpredictable. Agreement on U-factor is generally much closer. Glazing system 11 (double reflective, 12mm argon) has a 19% larger SHGC when based on the W5 spectrum compared with using EnergyPlus spectrum. Glazing system 15 displays an even bigger change: 23%.

Influence of chosen window model

Normalized results in Figures 4 – 11 show remarkable consistency across four disparate climates. For heating energy, the ranking of the 15 glazing systems is essentially independent of climate. Similarly, for cooling the ranking is also essentially invariant with climate, although the order is different from that of heating. In many cases there is much better agreement between the FSM and SWM than between the FSM and SAM. For heating in particular, the SAM almost always predicts a lower energy than the other two models – sometimes significantly less. We note that for tinted double-glazed systems, the FSM yields a significantly greater heating and cooling energy than both the other models.

CONCLUSIONS

As noted in the introduction, the Full Spectral Model is the preferred, 'benchmark' method of modeling windows in EnergyPlus, because it is the most advanced and detailed. In addition it is based on full, peer-reviewed IGDB spectral data. If this method is not an option – typically when only U, SHGC and VT are known for a window – then on the basis of this albeit limited study of 15 window systems and four temperate climates, we conclude that the Simple Window Model offers a reasonably good alternative to the Full Spectral Model. Arguably, the SWM is a better choice than the Spectral Average Model. We note however that the SWM is subject to limitations previous described, and it clearly remains a less-than-ideal choice compared with the Full Spectral Model.

Based on our sample which showed apparently poor agreement with the Full Spectral Model, we conclude that the Spectral Average Model nearly always under-predicts both heating and cooling energies. Under-prediction of heating energy exceeds 30% in some warmer climates. However we note that such an absolute error in predicted heating energy is less serious in such climates.

As noted in our Introduction, we did not evaluate the WINDOW 5 EnergyPlus Report (EPR) Model in this paper. The EPR model is based on a WINDOW 5 calculation which uses full spectral data for all glazing layers. That report can also contain detailed thermophysical information for custom framing components previously modeled in THERM 5.2. Thus, we might expect the EPR method to yield results similar to, or possibly superior to, the Full Spectral Model within EnergyPlus. It is recommended that this hypothesis be investigated in a further study. We also recommend that *(i)* a wider sample of climates be used in a future study and *(ii)* building(s) be modeled with and without HVAC, so as to separate and quantify the impact of HVAC on the windows' annual energy performance.

The impact of different solar spectral weighting functions is of concern. Our results in Figure 1 show that, for some coated and tinted glazings, large apparent variations can occur in solar-optical properties. This introduces confusing discrepancies between performance ratings (U, SHGC, VT) and the reported values for the same parameters in building simulation tools. We recommend the worldwide adoption of a consistent, improved solar spectral function as a high priority. This would also eliminate the current discrepancy between the functions used in WINDOW 5 versus EnergyPlus.

ACKNOWLEDGMENTS

We acknowledge the helpful suggestions of Charlie Curcija in selecting the glazing systems used in this study.

REFERENCES

ABCB – Australian Building Codes Board. 2009. *Building Code of Australia*. www.abcb.gov.au.

Dariush Arasteh, Christian Kohler and Brent Griffith. October 2009. *Modeling Windows in EnergyPlus with Simple Performance Indices*. Paper LBNL2804.pdf, Lawrence Berkeley National Laboratory.

ASTM, 1987a. *Standard tables for terrestrial direct normal solar spectral irradiance for air mass 1.5. Standard E891-87*, American Society for Testing and Materials, West Conshohocken, PA, USA. www.astm.org.

ASTM, 1987b. *Standard tables for terrestrial solar spectral irradiance at air mass 1.5 for a 37_ tilted surface. Standard E892-87*, American Society for Testing and Materials, West Conshohocken, PA, USA. www.astm.org.

ASTM, 2003. *Standard tables for reference solar spectral irradiances: direct normal and hemispherical on 37_ tilted surface. Standard G173-03*. American Society for Testing and Materials, West Conshohocken, PA, Available from www.astm.org.

C.A. Gueymard and W.C. DuPont. 2009. *Spectral effects on the transmittance, solar heat gain, and performance rating of glazing systems*, Solar Energy **83**, 940–953.

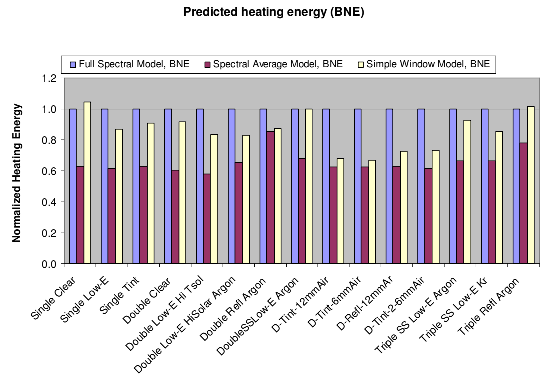
ISO, 1992. *Solar energy – reference solar spectral irradiance at the ground at different receiving conditions, pt. 1. International Standard 9845-1*, International Organization for Standardization, Geneva, Switzerland.

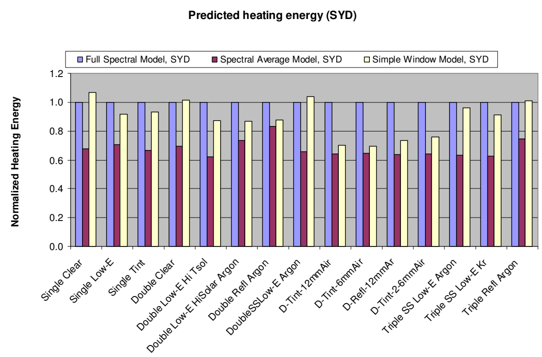
P.C. Thomas and D.K. Prasad. *Energy Efficient Building Envelopes - An Australian Perspective.* SOLARCH - National Solar Architecture Research Unit, University of New South Wales, Sydney 2052, Australia. Paper presented at Solar '94 Conference, Australian and New Zealand Solar Energy Society (ANZSES), UNSW (December 1994).

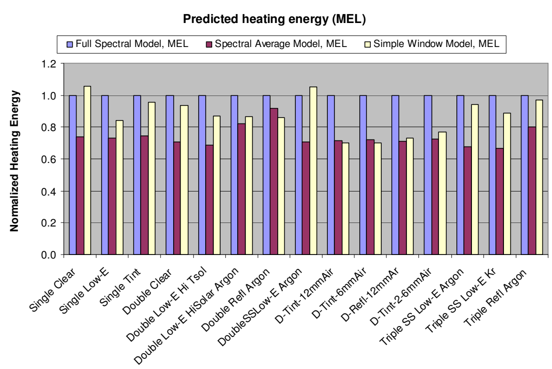
U.S. Department of Energy. 2009. www.energyplus.gov. *Input-Output Reference* and *Engineering Reference*, EnergyPlus V.4.0.

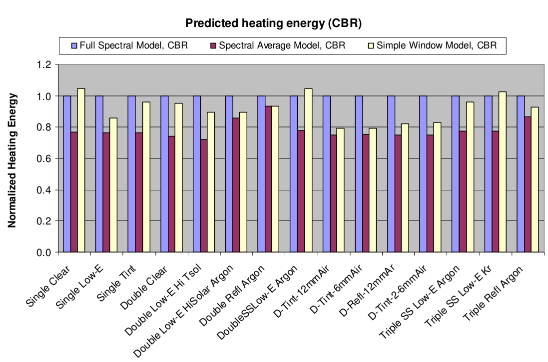
WINDOW 5.2 and THERM 5.2 simulation tools, Lawrence Berkeley National Laboratory. 2009. windows.lbl.gov/software.

Frederick C. Winkelmann. 2001. *Modeling Windows in EnergyPlus.* Simulation Research Group, EETD, Lawrence Berkeley National Laboratory, May 2001. Proc. *Building Simulation 2001*, IBPSA, Rio de Janeiro, September 2001.

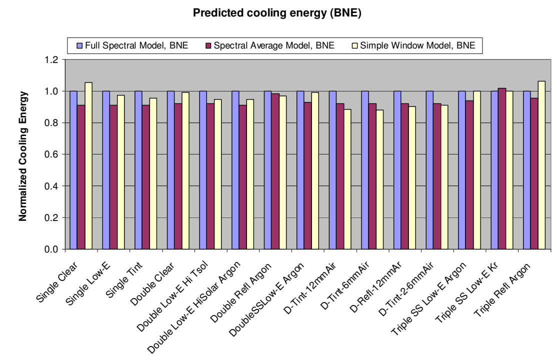


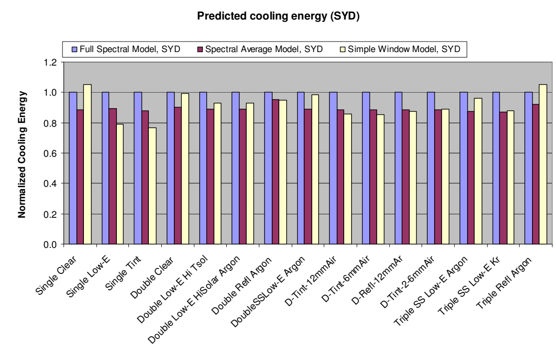


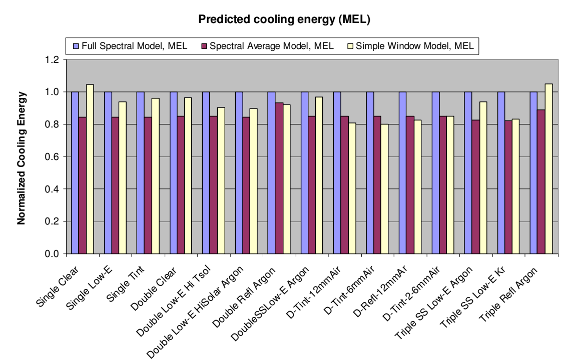


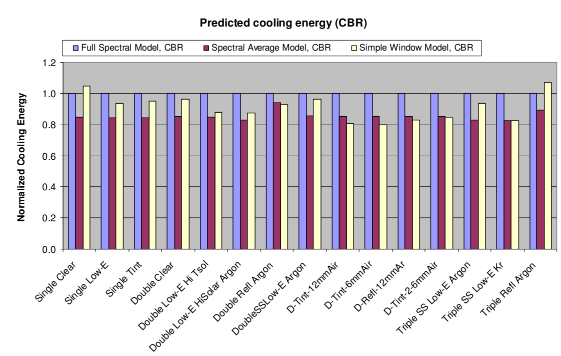


Above, Figures 4 - 7 (top to bottom): Annual heating energy, normalized for each glazing system with respect to FSM, for 5-zone, 10-storey building in Brisbane, Sydney, Melbourne, Canberra.









Above, Figures 8 - 11 (top to bottom): Annual cooling energy, normalized for each glazing system with respect to FSM, for 5-zone, 10-storey building in Brisbane, Sydney, Melbourne, Canberra.