Component Modeling Methodology for Predicting Thermal Performance of Nonresidential Fenestration Systems

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ABSTRACT

Nonresidential fenestration systems have different characteristics from residential products and therefore require different treatment. A component modeling methodology has been developed and is presented in this paper to specifically address nonresidential fenestration products, from punched openings to site-built and assembled products. The basic premise of this methodology is that the manufacturer of each fenestration component (i.e., framing, glazing, and spacer manufacturer) is responsible for its own product, for which the performance is published in NFRC-certified product directory (CPD), while the overall performance of the fenestration system is determined using functions developed from a number of actual runs with real glazing and spacer systems. The methodology is based on four generic runs, incorporating the high and low end of performance (i.e., best/worst or B/W options). This methodology can be implemented in a software tool, which would pull component information from the CPD into its own database and would calculate thermal and solar-optical performance at the standard size as well as the actual product size. This way, not only responsibility for component performance is clearly defined, but also the input data about fenestration systems for building energy simulation is accurate and will lead to more precise prediction of peak loads and annual energy use. Implementation of this methodology within a nationally recognized rating program will allow for uniform and accurate representation of nonresidential fenestration systems, for both site-built and punched opening type of fenestration products, while still providing data for a prescriptive path in energy codes (e.g., performance at standard NFRC size).

INTRODUCTION

Nonresidential products have been included in the NFRC rating system within the framework of residential windows (NFRC 2001 procedures) with one notable exception—site-built products. Recognizing that site-built products are manufactured by several parties (i.e., frame components are manufactured separately from IGU) and often put together by an independent party (i.e., "glazing contractor" or "glazer"), NFRC has established separate procedures for these products and has developed a separate certification process for buildings having more than 10,000 square feet of fenestration. However, this process is still very similar to residential windows in that it requires a single responsible party, which is often fulfilled by the framing system manufacturer. This places an undue burden on one side, as their role in reality is limited to selling and delivering frame lineals that are then put together at the site and IGU manufactured by another party is put into the framing system.

The AAMA procedure for nonresidential products (AAMA 1998, 2003) introduced the concept of separate treatment of framing and IGU units, which was a step in the right direction. The AAMA procedure uses simulation to determine U-factors, SHGC, and VT of products with different glazing systems and spacers. Using different glazing systems, with U-factors in increments of 0.12 W/m^2·K (0.02 Btu/h·ft^2·°F), the frame cross sections are modeled using NFRC-approved software. Once all cross sections are analyzed, overall U-factors, SHGC, and VT are calculated and plotted on a graph with the vision area percentage on the x axis and a performance index (i.e., U-factor, SHGC, or VT) on the y axis. For 100% vision area, the U-factor is simply the center-of-glass value. The graphs incorporate linear distributions, and in order to draw a

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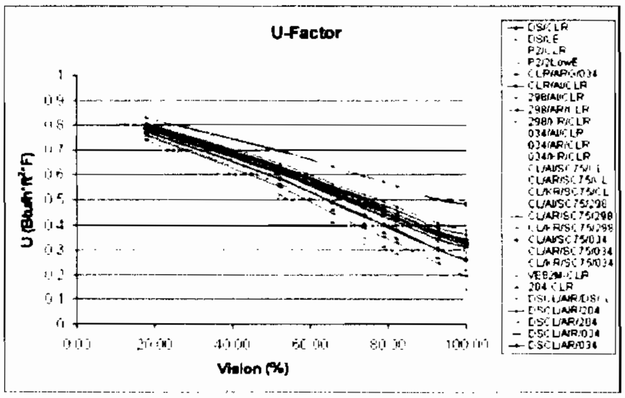

Figure 1 *Variation of U-factor with vision percentage.*

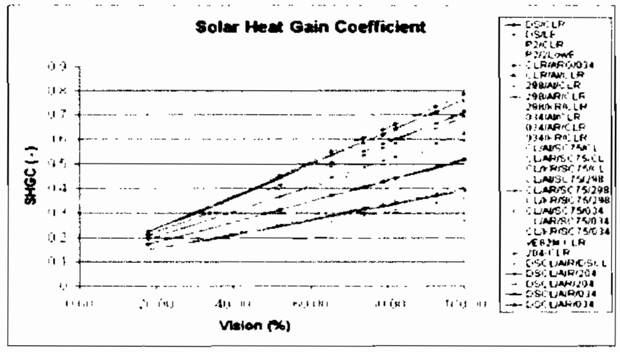

Figure 2 *Variation of solar heat gain coefficient with vision percentage.*

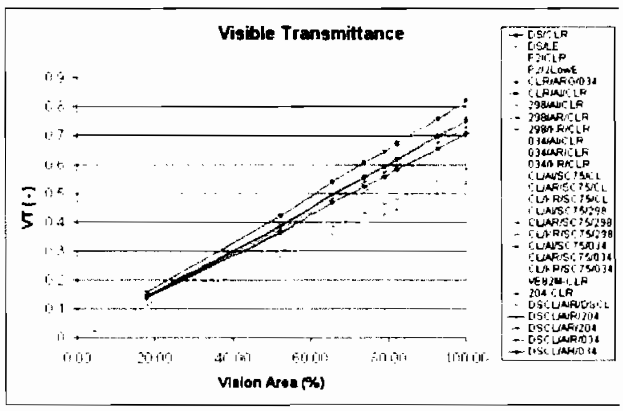

Figure 3 *Variation of visible transmittance with vision percentage.*

line for each glazing system, one other point at 70% vision area is calculated. For each spacer, the performance is recalculated and a graph is constructed. This method is somewhat cumbersome as it requires blocks of simulations for 15 different glazing options for each product line and separate blocks of simulations for each spacer design.

Within the last year, updated versions of the software tools THERM and WINDOW have been released. THERM 5.2 (Finlayson 2001; LBNL 2003a) and WINDOW 5.2 (LBNL 2003b) fully incorporate ISO 15099 methodology, which was published in 2003. The NFRC program and new standards specify use of THERM 5.2 and WINDOW 5.2 as the only approved software tools. Advanced radiation modeling is now required for all fenestration products that are certified through the NFRC system. Advanced, view factor-based, radiation modeling produces more accurate results for all products, but the difference is largest for higher conducting products, such as ordinary glazing, or/and aluminum frames. Testing standardization of results (NFRC 2001b) have also been modified and limited to the CTS method only in order to reflect more accurate simulation results.

COMPONENT METHODOLOGY

The component model approach is based on the assumption that the performance of the frame components and IGU, including spacer variations, can be modeled separately and then put together using interpolating curves. Investigation of the relations for the glazing system (i.e., center-of-glass performance) and size of the product indicate nearly linear relationship, which enables determination of the overall U-factor (or SHGC and VT) for an arbitrary size of the product using linear interpolation. Also, the performance of the overall product with different glazing systems can be described with a linear relationship, which enables determination of the overall product performance for an arbitrary glazing system by knowing its performance with two glazing options at the opposite end of thermal performance (i.e., "best" and "worst" IGU). In addition, spacer effects on the overall indices show logarithmic relationship when considered in terms of the effective conductivity of spacers, so the spacer effects can be calculated by modeling spacer options at the opposite ends of the thermal performance (i.e., "best" and "worst" spacers). These options can be modeled in conjunction with each other, creating a total of four best/worst, or "B/W, options (i.e., if using b and w for glazing best and worst and 1 and 2 for spacer best and worst cases, we have the following four options: b1, b2, w1, w2).

Figures 1 to 3 show relationship of center-of-glass performance (i.e., denoted by 100% vision area) to the total product performance, and it is evident that the curves are nearly linear. The largest departure from the linear relationship can be seen for U-factors; however, these departures are still very small as can also be seen from Figure 4, which shows linear fit and regression coefficients being around 0.997.

Further on, to accomplish a true component-based approach, the methodology has been scaled down to the most common denominator, which is a single cross-section assembly.

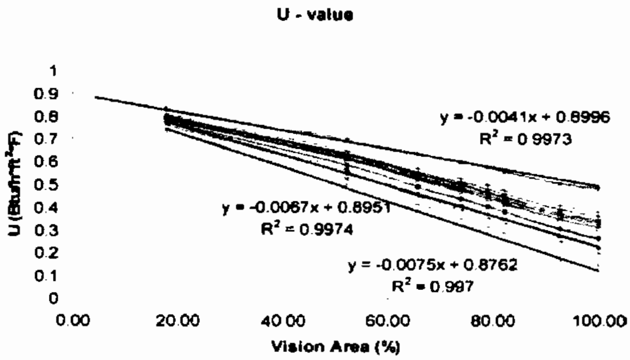

Figure 4 *Linear fit and regression coefficients for U-factor curves.*

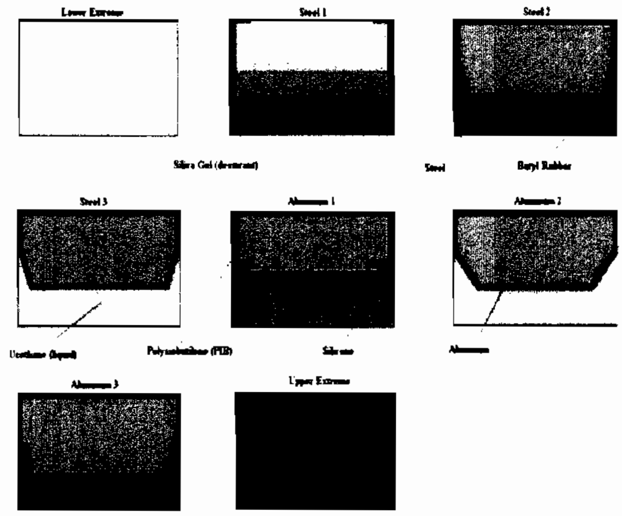

Figure 5 *Example of spacer configurations.*

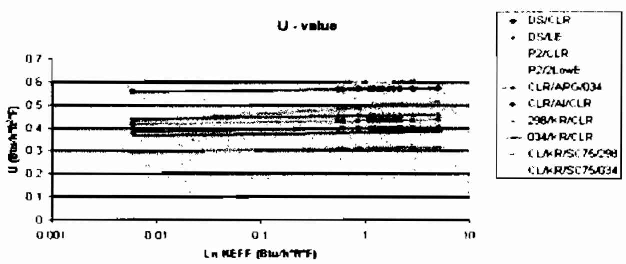

Figure 6 *Variation of U-factor with* k_{eff}.

In this approach, individual cross-section assemblies are simulated and this information is later used to "assemble" the finished product, which may be a simple, fixed, single window or it can be complex combination window consisting of several basic window shapes (e.g., two casement windows side by side with a fixed window over them) incorporated in a common frame.

Spacer Analysis

In order to analyze spacers, it was necessary to calculate their effective conductivity k_{eff} and to use that number to express their thermal performance. The calculation of k_{eff} of the spacer assembly was done according to the following procedure.

1. The overall U-factor of an individual spacer was calculated with THERM 5.2 using the following standard NFRC boundary conditions:

Exterior surface: $T_o = -18.00°C$ (–0.40°F), $h_o = 30.00$ W/m²·K (5.28 Btu/h·ft²·°F)

Interior surface: $T_i = 21.00°C$ (69.80°F), $h_i = 8.00$ W/m²·K (1.41 Btu/h·ft²·°F)

2. From the electrical analogy of resistances, the total heat flow resistance is

$$R_{tot} = \frac{1}{U} = \frac{1}{h_o} + \frac{L}{keff} + \frac{1}{h_i} . \qquad (1)$$

Effective conductivity k_{eff} can be determined as

$$keff = \frac{L}{R_{tot} - \frac{1}{h_o} - \frac{1}{h_i}} , \qquad (2)$$

where

L = spacer length,

R_{tot} = overall thermal resistance of a given spacer,

h_o = outside heat transfer coefficient, and

h_i = inside heat transfer coefficient.

Figure 5 shows an example of possible spacer configurations, including two fictitious entries representing low-end (high thermal conductance) and high-end (low thermal conductance) limits.

Using k_{eff} of a given spacer for the x axis and overall product U-factor, SHGC, and VT, and incorporating this spacer on the y axis, the logarithmic relationship results. Using logarithmic scale for the x axis, the curves have nearly linear distribution, confirming logarithmic distribution. Figures 6 to 8 show U-factor, SHGC, and VT distributions for selected glazing systems. Note that for VT, the relationship is linear, so the x axis in the graph in Figure 8 is linear rather than logarithmic.

ALGORITHM DEVELOPMENT

Based on the relationships shown above, the U-factor of a particular window, U (defined by a unique frame cross section and spacer type), is calculated as a function of four parameters: (1) center-of-glass U-factor, U_c of a window for which the U-factor is being sought; (2) U-factor of a window with the "worst" IGU, U_w; (3) U-factor of a window with the "best" IGU,

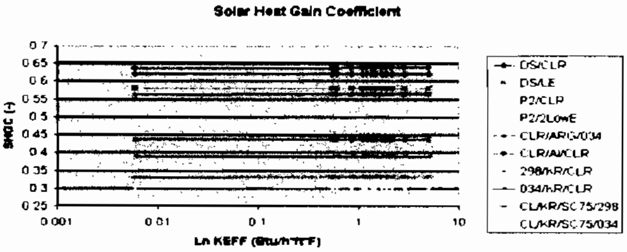

Figure 7 *Variation of solar heat gain coefficient with k_{eff}*

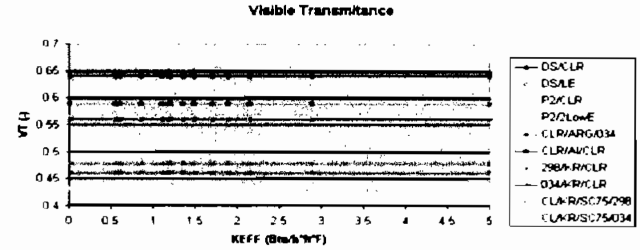

Figure 8 *Variation of VT (visible transmittance) with k_{eff}*

U_b; and (4) the size of a window for which the U-factor is being sought, being determined by a vision percentage V that in turn is calculated from the overall width and height of the window.

Having a linear relationship for the performance indices and having one point at the 100% vision area, it was important to select the second point at the lower vision percentage. It was decided that a 24-in.-by-24-in. window represents a reasonable lower size limit and a corresponding vision percentage area was developed for each of the unique window operator types. These dimensions (24 in. by 24 in.) are labeled "base dimensions."

The following equation gives the U-factor of a fenestration system in terms of "best" and "worst" glazing and spacers, denoted here as "B/W options":

$$U = U_b + \frac{(U_w - U_b)\cdot(U_c - U_{c,b})}{U_{c,w} - U_{c,b}} + \frac{\left(U_c - U_b + \frac{(U_w - U_b)\cdot(U_c - U_{c,b})}{U_{c,w} - U_{c,b}}\right)\cdot(V - V_1)}{100 - V_1} \quad (3)$$

where

U_w = U-factor of a window with base dimensions, incorporating "worst" IGU, determined from equations that follow

U_b = U-factor of a window with base dimensions, incorporating "best" IGU, determined from equations that follow

$U_{c,w}$ = center-of-glass U value for the "worst" IGU

$U_{c,b}$ = center-of-glass U value for the "best" IGU

U_c = center-of-glass U value of a window for which the U-factor is being calculated

V_1 = vision percentage of a window with base dimensions

V = vision percentage of a window for which the U-factor is being calculated

$$V = \frac{A_v}{A}\cdot 100 \quad (4)$$

where

A_v = vision area, calculated as

$$A_v = A - \sum_i A_{f,i} \quad (5)$$

$A_{f,i}$ = individual frame areas

A = total product area

$$A = a \cdot b \quad (6)$$

where

a = total window width

b = total window height

Note:

- "Worst" IGU was chosen to be double, clear, air-filled IGU, and "Best" IGU was chosen to be triple-glazed, double low-e, argon-filled IGU.
- Base window dimensions are 24 in. by 24 in.

The U-factors for a window incorporating "worst" IGU, U_w, and the U-factor for a window incorporating "best" IGU, U_b, is calculated using the following procedure:

$$U_w = U_{w1} + \frac{(U_{w2} - U_{w1})\cdot[\ln(keff) - \ln(keff_1)]}{\ln(keff_2) - \ln(keff_1)} \quad (7)$$

$$U_b = U_{b1} + \frac{(U_{b2} - U_{b1})\cdot[\ln(keff) - \ln(keff_1)]}{\ln(keff_2) - \ln(keff_1)} \quad (8)$$

where

U_{w1} = U-factor of window with standardized dimensions, "worst IGU," and "best spacer" (i.e., lowest conducting spacer assembly or lowest k_{eff}),

where

$$U_{w1} = \frac{\sum A_{fi-w1}\cdot U_{fi-w1} + \sum A_{ei-w1}\cdot U_{ei-w1} + A_{c,w}\cdot U_{c,w}}{A} \quad (9)$$

where i denotes cross section (i.e., sill, jamb, head, meeting rail, etc.)

U_{w2} = U-factor of window with standardized dimensions, "worst IGU," and "worst spacer" (i.e., highest conducting spacer assembly or highest k_{eff}),

Table 1. Required Information for Calculating Overall Product Indices

	Frame Cross Section				Spacer	Glazing
	w1	w2	b1	b2		
U_f[W/m^2·K]						
U_e [W/m^2·K]						
Pdf [m]						
Uc [W/m^2·K]						
Keff [W/m·K]						
SHGC [-]						
VT [-]						

Note: *pdf* is projected frame depth.

Table 2. Example of Label for Framing System

	w1			w2			b1			b2		
	U	SHGC	VT	U	SHGC	VT	U	SHGC	VT	U	SHGC	VT
Frame												
Edge of glass												
Pdf [m]												

Note: U-factor units are W/m^2·K (SI) and Btu/h·ft^2·°F (IP)

Table 3. Example of Label for Glazing System

	U	SHGC	VT
Center of Glass			

Note: U-factor units are W/m^2·K (SI) and Btu/h·ft^2·°F (IP)

Table 4. Example of Label for Spacer System

	k_{eff}
Spacer	

Note: k_{eff} units are W/m·K (SI) and Btu/h·ft·°F or Btu·in./h·ft^2·°F (IP)

where

$$U_{w2} = \frac{\sum A_{fi-w2} \cdot U_{fi-w2} + \sum A_{ei-w2} \cdot U_{ei-w2} + A_{c,w} \cdot U_{c,w}}{A} \quad (10)$$

U_{b1} = U-factor of window with standardized dimensions, "best IGU," and "best spacer" (i.e., lowest conducting spacer assembly or lowest k_{eff}),

where

$$U_{b1} = \frac{\sum A_{fi-b1} \cdot A_{fi-b1} + \sum A_{ei-b1} \cdot U_{ei-b1} + A_{c,b} \cdot U_{c,b}}{A} \quad (11)$$

U_{b2} = U-factor of window with standardized dimensions, "best IGU," and "worst spacer" (i.e., highest conducting spacer assembly or highest k_{eff}),

where

$$U_{b2} = \frac{\sum A_{fi-b2} \cdot U_{fi-b2} + \sum A_{ei-b2} \cdot U_{ei-b2} + A_{c,b} \cdot U_{c,b}}{A} \quad (12)$$

k_{eff1} = effective conductivity of the "best spacer"
k_{eff2} = effective conductivity of the "worst spacer"
k_{eff} = effective conductivity of the spacer in a window for which the U-factor is being calculated

In order to calculate U_{w1}, U_{w2}, U_{b1}, and U_{b2}, component U-factors (i.e., frame U-factors, U_f, and edge-of-glass U-factors, U_e) for each individual assembly are calculated for the four B/W options.

SHGC and VT of a particular window with base dimensions are calculated in the same manner as U-factors detailed in the equations above.

PERFORMANCE LABELING

The four B/W performance numbers for U-factors, SHGC, and VT, as well as center-of-glass indices and projected frame dimensions (useful in determining vision percentage area), and effective conductivity of spacer can be tabulated as shown in Table 1. From this information, performance at any size can be calculated. However, the more effective and rational approach in rating and labeling would be to have the manufacturer of each "component" provide the rating for the individual components, where components here are divided into three groups:

- Framing system
- Glazing system
- Spacer system

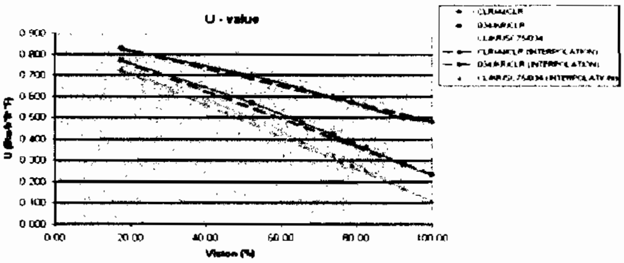

Figure 9 *Variation of U-factor with vision percentage.*

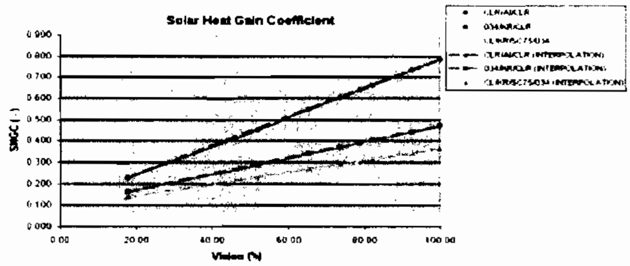

Figure 10 *Variation of SHGC with vision percentage.*

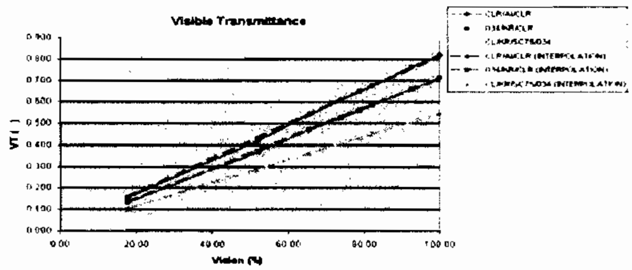

Figure 11 *Variation of VT with vision percentage.*

Note: Dividers are treated in the same manner as frame systems.

Labels with information for each of these component groups can be provided by a manufacturer, and the performance of the overall product can be performed by a third party (i.e., glazing contractor, architect, building official, Independent agency, etc.) using a computer tool that incorporates these algorithms and area weighting for different fenestration operator types (i.e., casement window, fixed window, horizontal slider, sliding doors, swinging doors, curtain wall, combination window, etc.). Table 2 shows an example of a rating label for the framing system. Table 3 shows an example of a label for a glazing system, and Table 4 shows an example of a label for a spacer system.

VALIDATION

U, SHGC, and VT, calculated for three representative glazing options using the detailed modeling approach with THERM and WINDOW are compared with corresponding values obtained from interpolation algorithm and plotted vs. vision percentage. Results are shown in Figures 9 to 11. It is evident from comparisons that the results obtained from interpolation compare very well with those obtained from detailed modeling. More comprehensive validation was done for three different window materials (aluminum, thermally broken aluminum, and fiberglass and vinyl-reinforced frames) and two different spacer materials.Results are presented in Tables 5 to 10. These tables present the total product indices, U-factor, SHGC, and VT determined using current NFRC-approved THERM/WINDOW programs and the component modeling algorithm described here. The results of the component modeling approach are labeled as FENSIZE and presented in a series of tables with corresponding results obtained from simulation using current THERM5/WINDOW5 procedures. TRR-97, TRR-99, TRR-01, and TRR-02 are NFRC testing round-robin specimens for the years 1997 and 1998, 1999 and 2000, and 2001 and 2002, respectively. Fiberglass and TR-4600 are additional products provided by manufacturers to cover all available products and materials. The difference between the results of the two approaches is shown in these tables with reference to FENSIZE results.

Tables 5 to 10 show that the results obtained from the two approaches are very close to each other. The maximum difference for different NFRC sizes is not more than 3% and 0.5%, respectively, for U-factor and SHGC, and there is no difference for VT; while for nonstandard NFRC sizes, the differences for U-factor and SHGC are not larger than 5% and 1%, respectively. In absolute terms for NFRC sizes, differences in U-factor calculated from both approaches are no greater than 0.01 Btu/h·ft^2·°F, for SHGC no greater than 0.001, and for VT there is no difference. For sizes other than NFRC standard sizes, the differences in U-factor are no greater than 0.02 Btu/h·ft^2·°F, for SHGC no greater than 0.001, and for VT there is no difference.

This component modeling procedure has been incorporated into the computer tool FENSIZE (Carli 2003). For more information about the tool, visit the following Web site: http://www.fenestration.com/fensize.htm.

CONCLUSIONS

The approach for modeling nonresidential products, described in this paper, offers simple and effective means for determining overall thermal and solar-optical performance of fenestration products. A comprehensive validation study, covering a wide range of framing materials and spacer types, shows that the performance indices calculated from this approach compare well with detailed traditional modeling procedures, which require full numerical modeling of each glazing and spacer option as incorporated into the window. Because this methodology requires only four generic glazing and spacer

Table 5. TRR-01—Thermally Broken Aluminum Frame Window (Fixed)

Model	Glazing System	Spacer	Size (in.	U (Btu/h·ft^2·°F)			SHGC (-)			VT (-)		
				T5/W5	FENSIZE		T5/W5	FENSIZE		T5/W5	FENSIZE	
TRR-01	clr/ar/clr (7/8 in.)	Standard Aluminum (5/8 in.)	36×24	0.532	0.527	-0.005	0.561	0.561	0.000	0.569	0.569	0.000
			48×36	0.510	0.507	-0.003	0.624	0.625	0.001	0.640	0.640	0.000
			47.244×59.055	**0.494**	**0.497**	**0.003**	**0.657**	**0.658**	**0.001**	**0.678**	**0.678**	**0.000**
			72×54	0.489	0.491	0.002	0.676	0.676	0.000	0.698	0.698	0.000
			96×72	0.476	0.483	0.007	0.702	0.703	0.001	0.728	0.728	0.000
		Insulating Foam (5/8 in.)	36×24	0.511	0.515	0.004	0.560	0.560	0.000	0.569	0.569	0.000
			48×36	0.494	0.498	0.004	0.624	0.624	0.000	0.640	0.640	0.000
			47.244×59.055	**0.482**	**0.490**	**0.008**	**0.657**	**0.658**	**0.001**	**0.678**	**0.678**	**0.000**
			72×54	0.478	0.485	0.007	0.675	0.676	0.001	0.698	0.698	0.000
			96×72	0.468	0.478	0.010	0.702	0.703	0.001	0.728	0.728	0.000
	034/ar/clr (7/8 in.)	Standard Aluminum (5/8 in.)	36×24	0.391	0.394	0.003	0.342	0.343	0.001	0.493	0.493	0.000
			48×36	0.352	0.354	0.002	0.379	0.379	0.000	0.555	0.555	0.000
			47.244×59.055	**0.332**	**0.333**	**0.001**	**0.398**	**0.399**	**0.001**	**0.587**	**0.587**	**0.000**
			72×54	0.320	0.321	0.001	0.409	0.409	0.000	0.605	0.605	0.000
			96×72	0.302	0.304	0.002	0.424	0.425	0.001	0.631	0.631	0.000
		Insulating Foam (5/8 in.)	36×24	0.373	0.378	0.005	0.342	0.342	0.000	0.493	0.493	0.000
			48×36	0.339	0.342	0.003	0.379	0.379	0.000	0.555	0.555	0.000
			47.244×59.055	**0.320**	**0.323**	**0.003**	**0.398**	**0.398**	**0.000**	**0.587**	**0.587**	**0.000**
			72×54	0.310	0.313	0.003	0.408	0.409	0.001	0.605	0.605	0.000
			96×72	0.295	0.298	0.003	0.424	0.424	0.000	0.631	0.631	0.000

Note: NFRC standardized dimensions are marked yellow.

Table 6. TRR-97—Aluminum Clad Wood Window (Fixed)

				U (Btu/h·ft^2·°F)			SHGC (-)			VT (-)		
Model	**Glazing System**	**Spacer**	**Size (in.)**	**T5/W5**	**FENSIZE**		**T5/W5**	**FEN-SIZE**		**T5/W5**	**FEN-SIZE**	
TRR-97	Clr/ar/clr (7/8 in.)	Standard Aluminum (5/8 in.)	36×24	0.490	0.485	-0.005	0.591	0.591	0.000	0.612	0.612	0.000
			48×36	0.480	0.477	-0.003	0.647	0.647	0.000	0.672	0.672	0.000
			47.244×59.055	**0.470**	**0.473**	**0.003**	**0.676**	**0.676**	**0.000**	**0.703**	**0.703**	**0.000**
			72×54	0.468	0.470	0.002	0.692	0.692	0.000	0.720	0.720	0.000
			96×72	0.461	0.467	0.006	0.714	0.715	0.001	0.745	0.745	0.000
		Insulating Foam (5/8 in.)	36×24	0.450	0.463	0.013	0.590	0.591	0.001	0.612	0.612	0.000
			48×36	0.450	0.461	0.011	0.646	0.647	0.001	0.672	0.672	0.000
			47.244×59.055	**0.447**	**0.460**	**0.013**	**0.675**	**0.676**	**0.001**	**0.703**	**0.703**	**0.000**
			72×54	0.448	0.460	0.012	0.691	0.692	0.001	0.720	0.720	0.000
			96×72	0.445	0.459	0.014	0.714	0.715	0.001	0.745	0.745	0.000
	034/ar/clr (7/8 in.)	Standard Aluminum (5/8 in.)	36×24	0.348	0.341	-0.007	0.357	0.357	0.000	0.530	0.530	0.000
			48×36	0.322	0.316	-0.006	0.390	0.390	0.000	0.582	0.582	0.000
			47.244×59.055	**0.306**	**0.303**	**-0.003**	**0.407**	**0.407**	**0.000**	**0.609**	**0.609**	**0.000**
			72×54	0.299	0.295	-0.004	0.417	0.417	0.000	0.623	0.623	0.000
			96×72	0.286	0.285	-0.001	0.430	0.430	0.000	0.645	0.645	0.000
		Insulating Foam (5/8 in.)	36×24	0.302	0.313	0.011	0.356	0.356	0.000	0.530	0.530	0.000
			48×36	0.288	0.296	0.008	0.389	0.390	0.001	0.582	0.582	0.000
			47.244×59.055	**0.279**	**0.287**	**0.008**	**0.406**	**0.407**	**0.001**	**0.609**	**0.609**	**0.000**
			72×54	0.275	0.282	0.007	0.416	0.416	0.000	0.623	0.623	0.000
			96×72	0.268	0.274	0.006	0.430	0.430	0.000	0.645	0.645	0.000

Note: NFRC standardized dimensions are marked yellow.

Table 7. TRR-99—Aluminum Window (Horizontal Slider)

Model	Glazing System	Spacer	Size (in.)	U (Btu/h·ft²·°F) T5/W5	FENSIZE		SHGC (-) T5/W5	FEN-SIZE		VT (-) T5/W5	FENSIZE	
TRR-99	clr/ar/clr (3/4 in.)	Standard Aluminum (1/2 in.)	36×24	0.687	0.682	-0.005	0.630	0.630	0.000	0.643	0.643	0.000
			48×36	0.621	0.618	-0.003	0.674	0.674	0.000	0.693	0.693	0.000
			59.055×47.244	**0.585**	**0.584**	**-0.001**	**0.697**	**0.697**	**0.000**	**0.720**	**0.720**	**0.000**
			72×54	0.564	0.565	0.001	0.710	0.710	0.000	0.735	0.735	0.000
			96×72	0.532	0.537	0.005	0.728	0.729	0.001	0.756	0.756	0.000
		Insulating Foam (1/2 in.)	36×24	0.676	0.677	0.001	0.630	0.630	0.000	0.643	0.643	0.000
			48×36	0.613	0.614	0.001	0.674	0.674	0.000	0.693	0.693	0.000
			59.055×47.244	**0.578**	**0.581**	**0.003**	**0.697**	**0.697**	**0.000**	**0.720**	**0.720**	**0.000**
			72×54	0.558	0.562	0.004	0.710	0.710	0.000	0.735	0.735	0.000
			96×72	0.528	0.535	0.007	0.728	0.729	0.001	0.756	0.756	0.000
	034/ar/clr (3/4 in.)	Standard Aluminum (1/2 in.)	36×24	0.540	0.536	-0.004	0.384	0.385	0.001	0.557	0.557	0.000
			48×36	0.459	0.454	-0.005	0.409	0.410	0.001	0.600	0.600	0.000
			59.055×47.244	**0.416**	**0.411**	**-0.005**	**0.423**	**0.423**	**0.000**	**0.623**	**0.623**	**0.000**
			72×54	0.390	0.386	-0.004	0.430	0.430	0.000	0.636	0.636	0.000
			96×72	0.353	0.351	-0.002	0.441	0.441	0.000	0.655	0.655	0.000
		Insulating Foam (1/2 in.)	36×24	0.526	0.529	0.003	0.384	0.384	0.000	0.557	0.557	0.000
			48×36	0.449	0.449	0.000	0.409	0.410	0.001	0.600	0.600	0.000
			59.055×47.244	**0.407**	**0.407**	**0.000**	**0.422**	**0.423**	**0.001**	**0.623**	**0.623**	**0.000**
			72×54	0.382	0.382	0.000	0.430	0.430	0.000	0.636	0.636	0.000
			96×72	0.347	0.348	0.001	0.440	0.441	0.001	0.655	0.655	0.000

Note: NFRC standardized dimensions are marked yellow.

Table 8. TRR-02—Thermally Improved Curtain Wall

Model	Glazing System	Spacer	Size (in.)	U (Btu/h·ft^2·°F)			SHGC (-)			VT (-)		
				T5/W5	FEN-SIZE		T5/W5	FEN-SIZE		T5/W5	FEN-SIZE	
Curtain wall	clr/ar/clr (1 in.)	Standard Aluminum (3/4 in.)										
			48×36	0.763	0.768	0.005	0.588	0.588	0.000	0.585	0.585	0.000
			59.055×47.244	**0.702**	**0.708**	**0.006**	**0.627**	**0.627**	**0.000**	**0.631**	**0.631**	**0.000**
			72×54	0.664	0.671	0.007	0.650	0.651	0.001	0.659	0.659	0.000
			96×72	0.611	0.621	0.010	0.683	0.683	0.000	0.698	0.698	0.000
		Insulating Foam (3/4 in.)										
			48×36	0.737	0.751	0.014	0.587	0.588	0.001	0.585	0.585	0.000
			59.055×47.244	**0.681**	**0.694**	**0.013**	**0.626**	**0.627**	**0.001**	**0.631**	**0.631**	**0.000**
			72×54	0.646	0.659	0.013	0.649	0.650	0.001	0.659	0.659	0.000
			96×72	0.597	0.612	0.015	0.682	0.683	0.001	0.698	0.698	0.000
	034/ar/clr (1 in.)	Standard Aluminum (3/4 in.)										
			48×36	0.634	0.638	0.004	0.364	0.364	0.000	0.506	0.506	0.000
			59.055×47.244	**0.561**	**0.564**	**0.003**	**0.385**	**0.386**	**0.001**	**0.547**	**0.547**	**0.000**
			72×54	0.516	0.519	0.003	0.398	0.398	0.000	0.571	0.571	0.000
			96×72	0.453	0.457	0.004	0.416	0.416	0.000	0.605	0.605	0.000
		Insulating Foam (3/4 in.)										
			48×36	0.604	0.618	0.014	0.363	0.363	0.000	0.506	0.506	0.000
			59.055×47.244	**0.536**	**0.548**	**0.012**	**0.384**	**0.385**	**0.001**	**0.547**	**0.547**	**0.000**
			72×54	0.495	0.505	0.010	0.397	0.398	0.001	0.571	0.571	0.000
			96×72	0.437	0.446	0.009	0.415	0.416	0.001	0.605	0.605	0.000

Note: NFRC standardized dimensions are marked yellow.

Table 9. Fiberglass Window (Casement)

Model	Glazing System	Spacer	Size (in.)	U ($Btu/h \cdot ft^2 \cdot °F$) T5/W5	U FENSIZE	U	SHGC (-) T5/W5	SHGC FENSIZE	SHGC	VT (-) T5/W5	VT FEN-SIZE	VT
Fiberglass	clr/ar/clr (1 in.)	Standard Aluminum (3/4 in.)	36×24	0.452	0.448	-0.004	0.521	0.521	0.000	0.534	0.534	0.000
			23.622×59.055	**0.452**	**0.449**	**-0.003**	**0.553**	**0.553**	**0.000**	**0.569**	**0.569**	**0.000**
			48×36	0.454	0.451	-0.003	0.595	0.595	0.000	0.614	0.614	0.000
			72×54	0.452	0.454	0.002	0.655	0.656	0.001	0.680	0.680	0.000
			96×72	0.449	0.456	0.007	0.687	0.687	0.000	0.714	0.714	0.000
		Insulating Foam (3/4 in.)	36×24	0.428	0.435	0.007	0.520	0.520	0.000	0.534	0.534	0.000
			23.622×59.055	**0.430**	**0.438**	**0.008**	**0.552**	**0.553**	**0.001**	**0.569**	**0.569**	**0.000**
			48×36	0.436	0.442	0.006	0.594	0.595	0.001	0.614	0.614	0.000
			72×54	0.440	0.448	0.008	0.655	0.656	0.001	0.680	0.680	0.000
			96×72	0.440	0.451	0.011	0.686	0.687	0.001	0.714	0.714	0.000
	034/ar/clr (1 in.)	Standard Aluminum (3/4 in.)	36×24	0.332	0.324	-0.008	0.316	0.316	0.000	0.462	0.462	0.000
			23.622×59.055	**0.326**	**0.316**	**-0.010**	**0.335**	**0.335**	**0.000**	**0.493**	**0.493**	**0.000**
			48×36	0.313	0.306	-0.007	0.360	0.360	0.000	0.532	0.532	0.000
			72×54	0.295	0.291	-0.004	0.395	0.395	0.000	0.589	0.589	0.000
			96×72	0.285	0.283	-0.002	0.414	0.414	0.000	0.618	0.618	0.000
		Insulating Foam (3/4 in.)	36×24	0.302	0.308	0.006	0.315	0.315	0.000	0.462	0.462	0.000
			23.622×59.055	**0.299**	**0.302**	**0.003**	**0.334**	**0.335**	**0.001**	**0.493**	**0.493**	**0.000**
			48×36	0.290	0.294	0.004	0.359	0.359	0.000	0.532	0.532	0.000
			72×54	0.279	0.283	0.004	0.395	0.395	0.000	0.589	0.589	0.000
			96×72	0.273	0.277	0.004	0.413	0.414	0.001	0.618	0.618	0.000

Note: NFRC standardized dimensions are marked yellow.

Table 10. TR-4600—PVC Window with Reinforcement (Vertical Double Hung)

Model	Glazing System	Spacer	Size (in.)	U (Btu/h·ft²·°F) T5/W5	U FENSIZE		SHGC (-) T5/W5	SHGC FEN-SIZE		VT (-) T5/W5	VT FEN-SIZE	
TR-4600	clr/ar/clr (7/8 in.)	Standard Aluminum (5/8 in.)	36×24	0.471	0.457	-0.014	0.487	0.486	-0.001	0.500	0.500	0.000
			48×36	0.466	0.457	-0.009	0.570	0.570	0.000	0.589	0.589	0.000
			47.244×59.055	**0.459**	**0.457**	**-0.002**	**0.615**	**0.615**	**0.000**	**0.638**	**0.638**	**0.000**
			72×54	0.461	0.457	-0.004	0.638	0.638	0.000	0.663	0.663	0.000
			96×72	0.456	0.457	0.001	0.673	0.674	0.001	0.701	0.701	0.000
		Insulating Foam (5/8 in.)	36×24	0.433	0.436	0.003	0.486	0.486	0.000	0.500	0.500	0.000
			48×36	0.438	0.442	0.004	0.569	0.570	0.001	0.589	0.589	0.000
			47.244×59.055	**0.438**	**0.445**	**0.007**	**0.614**	**0.615**	**0.001**	**0.638**	**0.638**	**0.000**
			72×54	0.441	0.446	0.005	0.638	0.638	0.000	0.663	0.663	0.000
			96×72	0.441	0.449	0.008	0.673	0.674	0.001	0.701	0.701	0.000
	034/ar/clr (7/8 in.)	Standard Aluminum (5/8 in.)	36×24	0.363	0.344	-0.019	0.295	0.295	0.000	0.433	0.433	0.000
			48×36	0.333	0.318	-0.015	0.344	0.344	0.000	0.510	0.510	0.000
			47.244×59.055	**0.312**	**0.304**	**-0.008**	**0.371**	**0.371**	**0.000**	**0.552**	**0.552**	**0.000**
			72×54	0.308	0.297	-0.011	0.385	0.385	0.000	0.574	0.574	0.000
			96×72	0.294	0.287	-0.007	0.406	0.406	0.000	0.607	0.607	0.000
		Insulating Foam (5/8 in.)	36×24	0.316	0.316	0.000	0.294	0.294	0.000	0.433	0.433	0.000
			48×36	0.298	0.298	0.000	0.344	0.344	0.000	0.510	0.510	0.000
			47.244×59.055	**0.286**	**0.289**	**0.003**	**0.371**	**0.371**	**0.000**	**0.552**	**0.552**	**0.000**
			72×54	0.283	0.284	0.001	0.384	0.385	0.001	0.574	0.574	0.000
			96×72	0.275	0.276	0.001	0.405	0.406	0.001	0.607	0.607	0.000

Note: NFRC standardized dimensions are marked yellow.

options to be modeled for any fenestration product that may incorporate an arbitrary number of glazing and spacers, it saves money and preserves simplicity for the manufacturer.

This methodology is equally suitable for the rating of the nonresidential products, as well as for the calculation of data that can be used in detailed building energy analysis. The component performance indices are easily assembled into the overall performance for the actual product size and configuration and utilized in building simulation programs.

This approach allows each component manufacturer to provide performance information for its own products, calculated independently from other components. Also, the component-rating responsibility lies with each component manufacturer, where labels with information for each individual component group (i.e., framing, glazing, and spacer systems) can be provided by the manufacturer, while the performance of the overall product can be determined by a third party (i.e., glazing contractor, architect, building official, independent agency, etc.).

This methodology can be incorporated into the computer tool, which would provide a uniform and credible environment for determining overall product performance. This tool would incorporate algorithms presented in this paper and area weighting for different fenestration operator types (i.e., casement window, fixed window, horizontal slider, sliding doors, swinging doors, curtain wall, combination window, etc.).

This simplified and yet accurate approach can easily be adopted by rating organizations, and the certification process can be Web-based, utilizing a database structure and therefore easily accessed by users.

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