

Fenestration Optimization for Commercial Building Energy Standards

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ABSTRACT

This paper presents a method of developing glazing criteria for a proposed addendum to ASHRAE/IES Standard 90.1. The process builds on that used to develop ASHRAE Standard 90.2P, which found the optimal value of one performance measure (i.e., U-value) relative to two climatic variables. The optimization process for commercial glazing is more complex because there are three significant performance characteristics: thermal transmittance (U-value), shading coefficient (SC), and visible light transmission (T_{vis}).

A computer simulation tool was used to evaluate a set of fenestration assemblies in 36 climatic zones. A regression analysis of these computer-generated data provided a simple energy model for use in the optimization.

The simple energy model and a window cost model were used to evaluate all reasonable glazing choices. An algorithm was developed that yields the optimal fenestration choice based on the occupancy pattern of the building, the window/wall ratio, the desired interior lighting level, and two climatic variables.

INTRODUCTION

The optimization procedure presented in this paper was developed in order to set commercial fenestration criteria based on minimum life-cycle cost. Many current codes and standards set requirements based on an overall building target, essentially ignoring the cost-effectiveness of the resulting construction. For example, in ASHRAE 90.1, the envelope criteria are based on a window-wall ratio between 24% and 40%, depending on climate and internal gain. As a result, small window areas allow lower energy performance, and large window areas are allowed only with more expensive, high-performance windows. In some cases, cost-effective energy savings are wasted in the buildings with small glass areas, and windows that are not cost-effective are required in buildings with larger fenestration area. In the methodology described here, the optimum fenestration construction may be calculated for any window-wall ratio, allowing the criteria to be set at the cost-effective level for all window areas.

This methodology also considers the benefits of daylighting by including lighting energy savings as well as heating and cooling savings in the energy model. Many

current codes for commercial fenestration focus primarily on cooling energy (and, therefore, shading coefficient) while ignoring the potential benefits of daylighting.

Methodology

The proposed fenestration criteria are developed through life-cycle cost analysis of all reasonable fenestration constructions. The optimization combines an energy use model with a construction cost model to calculate the cost-effective glazing choice for a given window-wall ratio (WWR). The simple energy model accounts for the total performance of the fenestration construction with consideration of thermal transmittance (U-value), shading coefficient (SC), and visible light transmission (T_{vis}) together.

Life-Cycle Cost

For a given set of climatic conditions, the fenestration criteria are set equal to the performance of the fenestration construction with the lowest relative life-cycle cost. Relative life-cycle cost is used because it is only necessary to account for those elements that change between one construction and the next. The relative life-cycle cost of a glazing construction is calculated with Equation 1:

$$\text{LCC}_i = \text{COST}_i \cdot \text{WWR} + PV_e \\ \cdot \text{kWh}_i + PV_g \cdot \text{Therms}_i \quad (1)$$

where

LCC_i	= relative life-cycle cost of the i th fenestration construction per square foot of wall area ($$/\text{ft}^2$),
COST_i	= construction cost of the i th fenestration construction per square foot of glass ($$/\text{ft}^2$),
WWR	= window-wall ratio (unitless),
PV_e	= present value of a kilowatt-hour per year of electricity used over the life of the building ($$/\text{kWh}$),
kWh_i	= annual electricity use of the building with the i th fenestration construction per square foot of wall area (kWh/ft^2),
PV_g	= present value of a therm of natural gas used each year over the life of the building ($$/\text{kWh}$),

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TABLE 1
Energy Regression Coefficients for Equations 2 and 3

Building Type	Orientation	C ₃	C ₄	H ₂	H ₃
Low Gain	Combined	2.49E-03	1.31E-02	3.19E-04	-2.12E-04
Commercial	N	4.92E-04	5.70E-03	3.09E-04	-1.03E-04
	S	3.13E-03	1.60E-02	3.04E-04	-2.40E-04
	E	2.86E-03	1.47E-02	3.13E-04	-1.89E-04
	W	3.38E-03	1.56E-02	3.14E-04	-2.03E-04
High Gain	Combined	4.37E-03	1.30E-02	3.38E-04	-2.23E-04
Commercial	N	1.14E-03	4.96E-03	3.03E-04	-9.15E-05
	S	4.45E-03	1.27E-02	2.92E-04	-9.15E-05
	E	4.18E-03	1.17E-02	3.03E-04	-1.69E-04
	W	4.51E-03	1.22E-02	3.02E-04	-1.79E-04
Residential/	Combined	2.84E-03	1.08E-02	3.18E-04	-2.27E-04
Hotel	N	5.29E-04	4.75E-03	3.10E-04	-1.11E-04
	S	3.44E-03	1.32E-02	3.05E-04	-2.58E-04
	E	3.15E-03	1.22E-02	3.14E-04	-2.00E-04
	W	4.11E-03	1.26E-02	3.15E-04	-2.16E-04

Therms_i = the annual gas use of the building with the *i*th fenestration construction per square foot of wall area (therms/ft²).

The present value terms used in the analysis are \$0.96/kWh and \$6.72/therm. These assume energy costs of \$0.08/kWh and \$0.56/therm along with a real discount rate of 3% and building life of 15 years. The present value factors also correspond to a real discount rate of 6% and lifetime of 22 years.¹

Heating and Cooling Energy

Electricity and natural gas use are calculated with regression equations that take into account, not only the fenestration performance, but also the heating and cooling degree-days for a particular location (see Equations 2 and 3).

$$\text{Therms}_i = h_0 + h_1 \cdot \text{HDD}_{65} + h_2 \cdot \text{WWR} \cdot \text{HDD}_{65} \quad (2)$$

$$\cdot U_i + h_3 \cdot \text{WWR} \cdot \text{HDD}_{65} \cdot SC_i$$

$$\text{kWh}_i = c_0 + c_1 \cdot \text{HDD}_{65} + c_2 \cdot \text{CDD}_{65} + c_3 \cdot \text{WWR} \quad (3)$$

$$\cdot \text{HDD}_{65} \cdot SC_i + c_4 \cdot \text{WWR} \cdot \text{CDD}_{65} \cdot SC_i + \text{kWh}_{light}$$

where

- WWR = window-wall ratio (unitless),
- U_i* = U-value of the *i*th fenestration construction (Btu/[h·ft²·°F]),
- SC_i = shading coefficient of the *i*th fenestration construction (unitless),
- HDD₆₅ = heating degree-days at base 65°F (18.3°C) for a particular climatic zone,
- CDD₆₅ = cooling degree-days at base 65°F (18.3°C) for a particular climatic zone,
- kWh_{light} = lighting energy in the perimeter zone per square foot of wall area (discussed in the next section),
- c_n, h_n = coefficients determined through regression analysis (see Table 1).

In comparing fenestration constructions in a given climate, the coefficients *h₀*, *h₁*, *c₀*, *c₁*, and *c₂* are not significant because the associated terms cancel each other when two or more fenestration constructions are compared. Only the significant coefficients (*h₂*, *h₃*, *c₃*, and *c₄*) are presented in this paper (see Table 1). These coefficients are presented for three building use patterns: a high-gain commercial building with 3.5 W/ft² (38 W/m²) total lighting and equipment load, a low-gain commercial building with 1.75 W/ft² (19 W/m²), and a residential type occupancy with 1.65 W/ft² (18 W/m²) that is continuously operated. Both the high- and low-gain commercial buildings are assumed to be operated about 12 hours a day Monday through Friday and half a day on Saturday.

The energy use coefficients are calculated through regression analysis of DOE2.1D computer simulation

¹This method does not account for time-of-use utility rates since they would add significantly to the complexity of the analysis. In addition, Equation 1 does not include an extra term for peak electricity demand charges or for savings due to HVAC system down-sizing. These factors are not considered for the sake of simplicity, and their impact on the relative ranking of fenestration constructions could be a subject for further study.

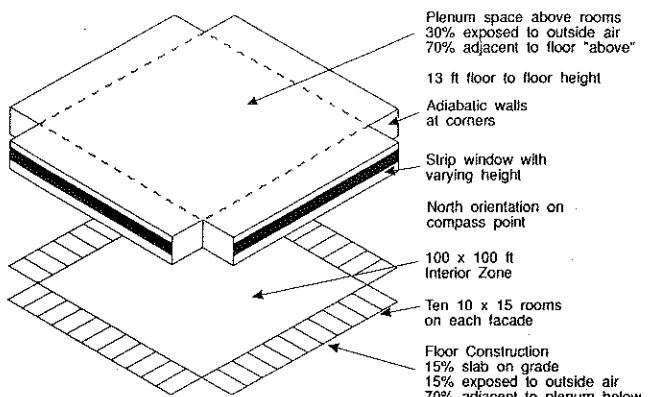


Figure 1 Five-zone computer model used in DOE-2 analysis.

results. The building model used for these runs is a simple five-zone building shown in Figure 1, and the regressions are performed for each orientation as well as all zones combined. The computer runs are performed for 36 climates (see Table 2). For each climate, the performance of seven fenestration constructions, with U-values ranging from $1.21 \text{ Btu}/(\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F})$ ($6.76 \text{ W}/[\text{m}^2\cdot{}^\circ\text{C}]$) to 0.48 (2.73) and shading coefficients ranging from 0.81 to 0.16 , are simulated. Assumptions about the remainder of the building envelope include an R-19 insulated roof, R-11 insulated metal frame walls, and R-11 insulation under the exposed portion of the floor. No daylighting controls are assumed in these simulations; the electricity savings due to daylighting are calculated separately, as described in the next section.

Each of the five zones is assumed to be served by its own constant-volume packaged gas/electric HVAC system, probably the most common system type in commercial construction. The system includes a non-integrated economizer with a 60°F (15.6°C) setpoint. The heating thermostat setpoint is 70°F (21.1°C), and the cooling setpoint is 75°F (23.9°C). Single-zone systems are necessary in the computer modeling in order to tabulate results by orientation.

Figures 2 through 7 compare the results of the regression equations to the DOE-2 results. If there were perfect agreement, all the points would occur along the diagonal lines. Points above the diagonal line are cases where the gas or electricity use predicted by the regression equations is greater than that predicted by DOE-2. Points below the line represent cases when the regression prediction is less than DOE-2. These graphs are for the whole building regression equations. The fit for the orientation-specific regression equations is not as good, with R-squared values ranging from 0.96 to 0.99 for heating and 0.85 to 0.95 for cooling. (The results might improve if a weather term accounting for solar radiation were added to the regression equation.)

Lighting Energy

The choice of fenestration can also have an impact on the energy required for electric lighting, and this is ac-

counted for in the optimization. Consideration of the daylighting benefits gives an advantage to fenestration with a high visible light transmission, all other things being equal. The electric energy requirement for lighting can be calculated with Equation 4. This is added to the electricity use predicted by Equation 3.

$$\text{kWh}_{light} = \frac{P_L \cdot H_L (1 - K_d)}{1000} \quad (4)$$

where

- kWh_{light} = annual electricity used for lighting per square foot of wall area ($\text{kWh}/[\text{yr}\cdot\text{ft}^2]$);
 P_L = lighting power in the perimeter zone per square foot of wall area (W/ft^2);
 H_L = annual hours of lighting operation with no consideration of daylighting savings (h/yr), assumed to be 2,700 hours in this analysis;
 K_d = daylight savings fraction from Equation 5 (unitless).

With continuously dimming daylighting controls, the daylight savings fraction in a perimeter space can be explained in terms of the window-wall ratio, the visible light transmission of the fenestration, and the design illumination. The relationship between these variables is documented in Sullivan (1988) as

$$K_d = \left[\phi_1 + \phi_2 (C / T_{vis_i}) \right] \left[1 - e^{(\phi_3 + \phi_4 \cdot C) \text{WWR} \cdot T_{vis_i}} \right] \quad (5)$$

where

- T_{vis_i} = visible light transmission of the i th fenestration construction (unitless),
 WWR = window-wall ratio (unitless),
 C = design illumination (footcandles),
 ϕ_n = coefficients listed in Table 3.

TABLE 2
Cities Used in Regression Analysis

Adak, AK	Fort Smith, AR	Las Vegas, NV
Albuquerque, NM	Fort Worth, TX	Los Angeles, CA
Bangor, ME	Fresno, CA	Madison, WI
Bismarck, ND	Honolulu, HI	Miami, FL
Brownsville, TX	St Louis, MO	Omaha, NE
Bryce Canyon, UT	Tucson, AZ	Phoenix, AZ
Central Park, NY	Washington, DC	Redmond, OR
Charleston, SC	Winnemucca, NV	Roswell, NM
Denver, CO	Jacksonville, FL	Sacramento, CA
Dodge City, KS	Kwajalein Island, PN	San Diego, CA
El Paso, TX	Lake Charles, LA	San Francisco, CA
Fairbanks, AK	Laredo, TX	Seattle, WA

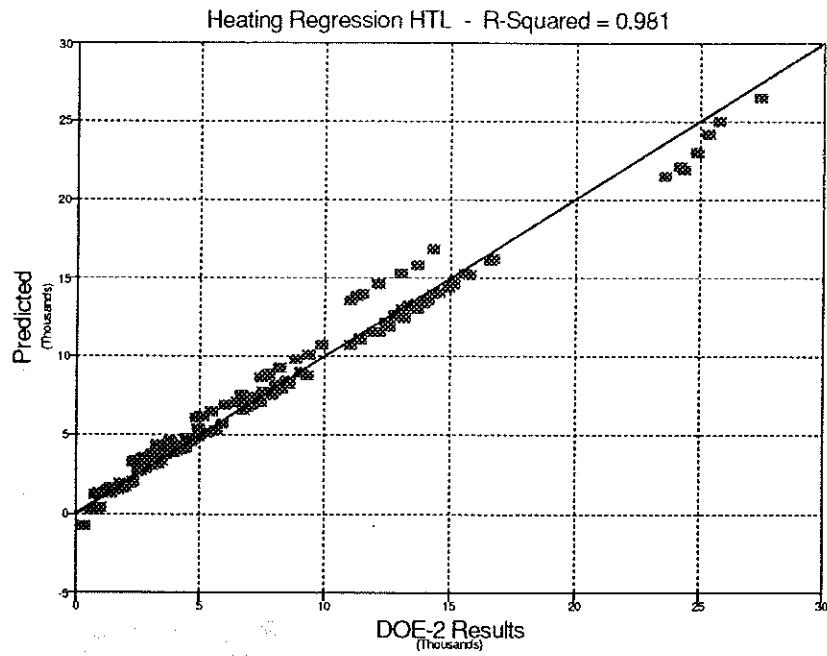


Figure 2 Heating regression results for hotels. Compares predicted results using Equation 2 to DOE-2 simulation results. Units in thousands of therms of natural gas.

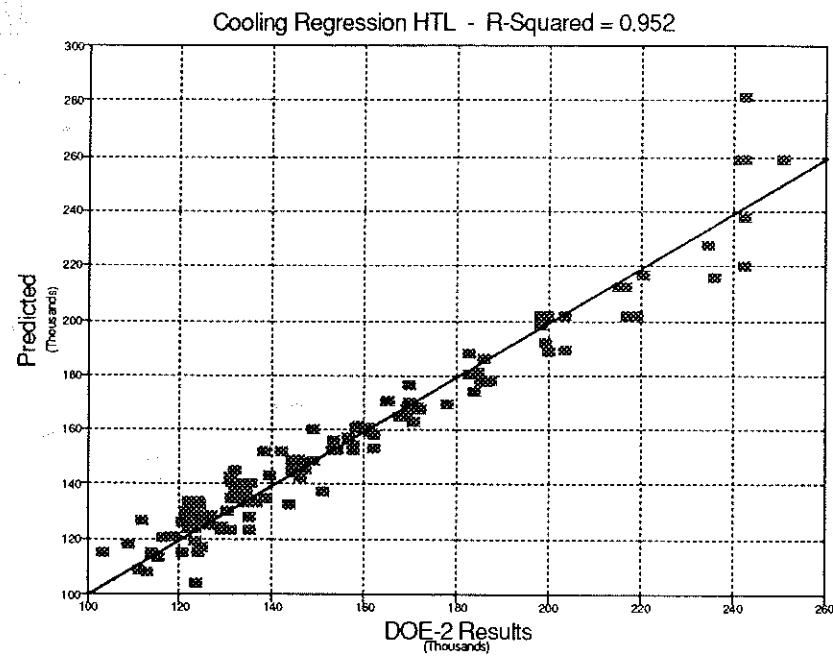


Figure 3 Cooling regression results for hotels. Compares predicted results using Equation 3 to DOE-2 simulation results. Units in thousands of kWh.

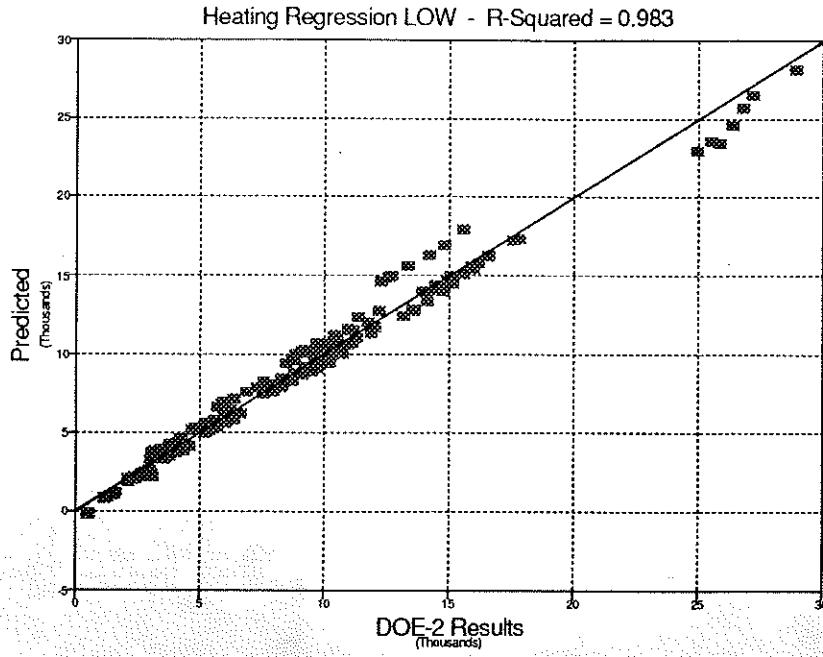


Figure 4 Heating regression results for low internal gain offices. Compares predicted results using Equation 2 to DOE-2 simulation results. Units in thousands of therms of natural gas.

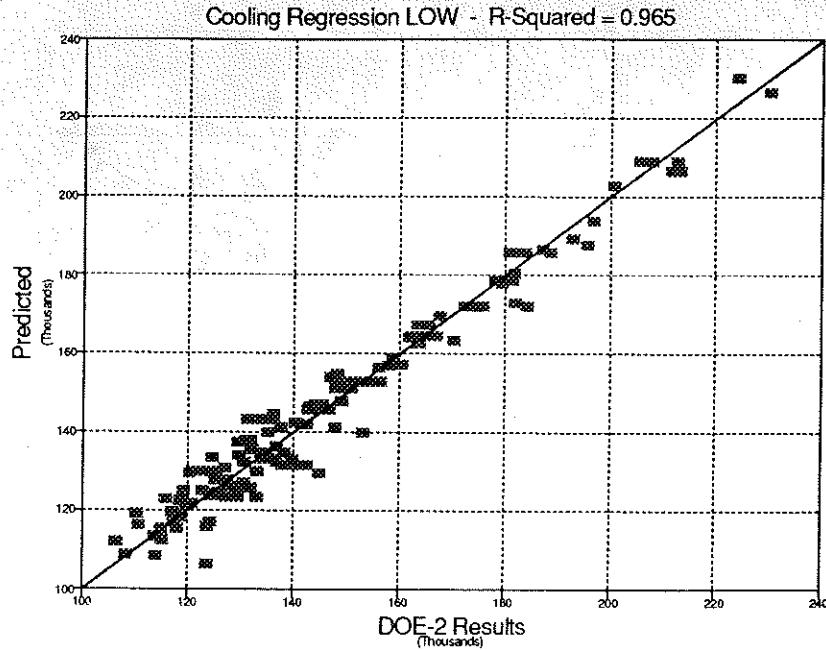


Figure 5 Cooling regression results for low internal gain offices. Compares predicted results using Equation 3 to DOE-2 simulation results. Units in thousands of kWh.

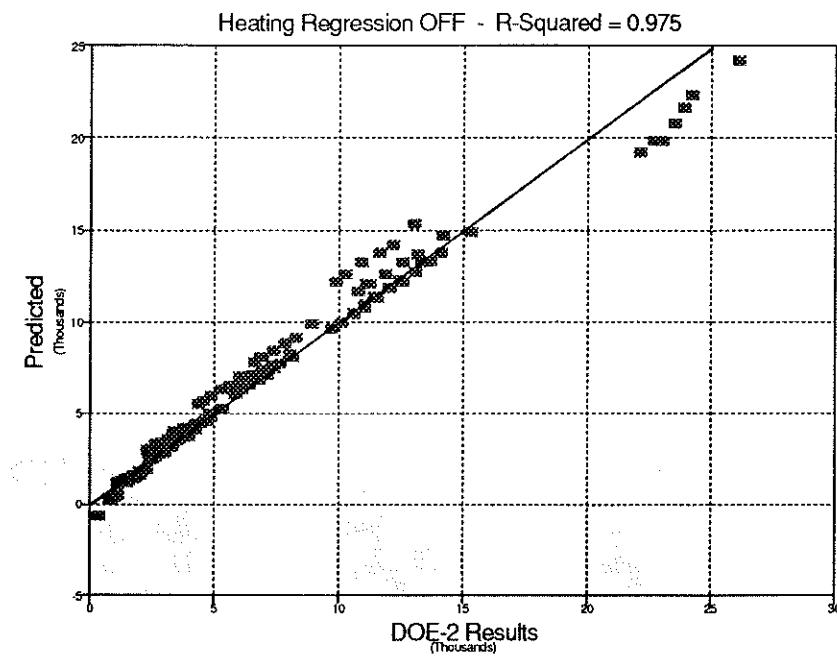


Figure 6 Heating regression results for high internal gain offices. Compares predicted results using Equation 2 to DOE-2 simulation results. Units in thousands of therms of natural gas.

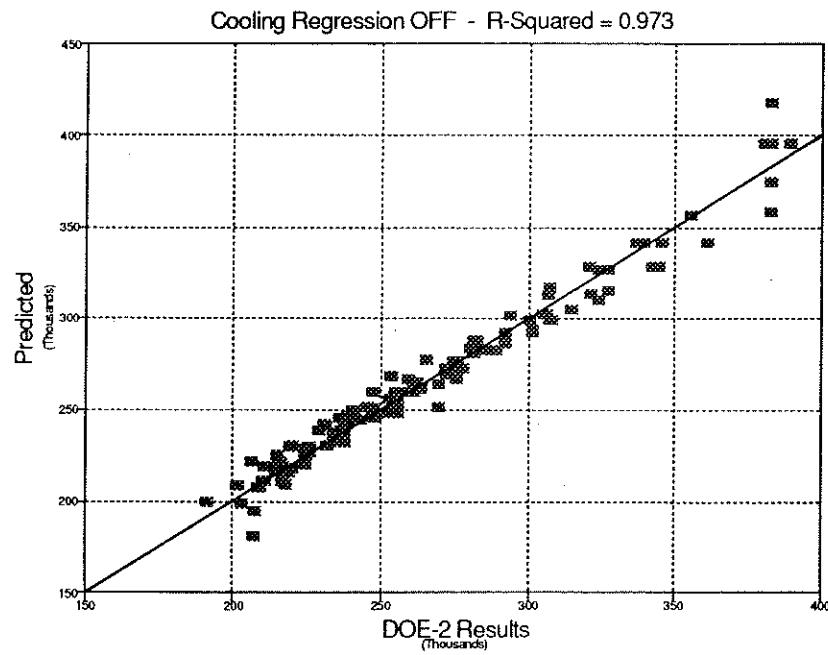


Figure 7 Cooling regression results for high internal gain offices. Compares predicted results using Equation 3 to DOE-2 simulation results. Units in thousands of kWh.

TABLE 3
Daylighting Coefficients for Equation 5

Values Used in the Analysis	Madison	Lake Charles
ϕ_1	.737	.737
ϕ_2	-.000317	-.000317
ϕ_3	-24.71	-20.818
ϕ_4	.234	.201
		.266

The coefficients used in the LCC analysis are listed in Table 3.

The thermal impact of reduced lighting energy is not accounted for in the equations. However, as lighting energy is reduced through daylighting, the cooling loads are also reduced (while heating loads increase). The thermal benefit of daylighting can result in cooling savings equal to 10% to 30% of the direct lighting savings (depending on climatic conditions). This interaction is not accounted for in the equations but could be a subject for further development. Consideration would increase the benefits associated with fenestration constructions with a high visible light transmission since cooling is more significant than heating in most commercial buildings.

Climate Boundaries

Equation 1 enables the relative life-cycle cost of fenestration constructions to be calculated for a specific set of climatic conditions. This may be repeated for all applicable fenestration constructions, and the one with the lowest life-cycle cost may be selected and used as the basis of the criteria for those climatic conditions.

It is also desirable to determine the climate boundaries between one fenestration construction and another. The boundary condition between two fenestration constructions, say the i th and the j th constructions, occurs when the relative life-cycle cost of the two constructions is equal, as shown in Equation 6.

$$LCC_i = LCC_j \quad (6)$$

By substituting Equations 1 through 5 into Equation 6, the climatic variable intercepts that define the boundary condition between the two fenestration constructions can be determined. First, HDD_{65} is set to zero and the equation is solved for CDD_{65} . Next, CDD_{65} is set to zero and the equation is solved for HDD_{65} . Equations 7 and 8 describe the heating and cooling degree-day intercepts between two constructions for a given window wall ratio.

$$HDD_{65}(i,j) = \frac{\left[\begin{array}{l} WWR(COST_j - COST_i) \\ -PV_e(kWh_{light_j} - kWh_{light_i}) \end{array} \right]}{\left[\begin{array}{l} PV_e \cdot WWR c_3(SC_i - SC_j) \\ +PV_g \cdot WWR[h_1(U_i - U_j) + h_2(SC_i - SC_j)] \end{array} \right]} \quad (7)$$

$$CDD_{65}(i,j) = \frac{\left[\begin{array}{l} WWR(COST_j - COST_i) \\ -PV_e(kWh_{light_j} - kWh_{light_i}) \end{array} \right]}{PV_e \cdot WWR \cdot C_4(SC_i - SC_j)} \quad (8)$$

where

$HDD_{65}(i,j)$ = heating degree-day (base 65°F [18°C]) intercept for cost-effectiveness boundary between fenestration constructions i and j ,

$CDD_{65}(i,j)$ = cooling degree-day (base 65°F [18°C]) intercept for cost-effectiveness boundary between fenestration constructions i and j .

Other terms were previously defined.

Fenestration Constructions

One hundred and four fenestration constructions were considered in the life-cycle cost optimization. These constructions include combinations of the following:

- Standard metal framing, metal framing with a thermal break, and vinyl frames.²
- Single and double glass.
- Clear, bronze, green, and high-performance tinted glass for the outer lite.
- Clear, green, and high-performance tinted glass for the inner lite.
- Low-emissivity coating on the second surface, the third surface, or both.
- Low-e coated mylar film suspended between double panes of clear glass.
- Medium- and high-performance reflective coatings on the second surface.

Table 4 lists the 21 fenestration constructions, out of the total of 104, that show up as optimal choices. The table also shows the assumed unit cost (\$/ft²), the shading coefficient (SC), the visible light transmission (T_{vis}), and the U-value.

²Wood frames are not explicitly considered in the analysis because their energy performance is comparable to vinyl frames while their initial cost is generally higher. Therefore, wood frames would not be cost-effective using this methodology when compared to vinyl frames. While wood frames are energy efficient, other design considerations also lead to their use.

TABLE 4
Fenestration Construction Reference
for Figures 8 Through 12

Number	Construction	Cost	SC	Tvis	U-Value (IP)	U-Value (SI)
1	single-pane clear, metal frame	0.00	0.95	0.88	1.21	6.87
2	single-pane green tint, metal frame	0.51	0.71	0.75	1.21	6.87
3	single-pane high performance tint, metal frame	1.43	0.61	0.72	1.21	6.87
4	single-pane green tint with high performance reflective coating, metal frame	2.86	0.25	0.07	1.01	5.74
5	double-pane clear, metal frame	3.93	0.81	0.78	0.71	4.03
6	double-pane green outer/clear inner, metal frame	4.43	0.57	0.66	0.71	4.03
7	double-pane high performance tint outer/clear inner, metal frame	5.36	0.47	0.64	0.71	4.03
8	double-pane high performance tint outer/clear inner, low-e on #2 surface, metal frame	7.80	0.39	0.59	0.58	3.29
9	double-pane green outer/clear inner, high perf. reflective coating on #2 surface, metal frame	6.79	0.18	0.06	0.64	3.64
10	double-pane green outer/clear inner, high perf. reflective coating on #2 surface, low-e on #3 surface, metal frame	9.23	0.14	0.06	0.58	3.29
11	double-pane clear with suspended mylar film, metal frame	12.18	0.18	0.25	0.48	2.73
12	double-pane clear, metal thermal break frame	5.88	0.81	0.78	0.58	3.29
13	double-pane green outer/clear inner, metal thermal break frame	6.38	0.57	0.66	0.58	3.29
14	double-pane green outer/clear inner, low-e on #2 surface, metal thermal break frame	8.83	0.49	0.62	0.45	2.56
15	double-pane high performance tint outer/clear inner, low-e on #2 surface, metal thermal break frame	9.75	0.39	0.59	0.45	2.56
16	double-pane green outer/clear inner, high perf. reflective coating on #2 surface, metal thermal break frame	8.74	0.18	0.06	0.51	2.90
17	double-pane clear with suspended mylar film, metal thermal break frame	14.13	0.18	0.25	0.35	1.99
18	double-pane high performance tint outer/clear inner, low-e on #2 surface, vinyl frame	13.00	0.39	0.59	0.34	1.93
19	double-pane clear with suspended mylar film, vinyl frame	17.38	0.18	0.25	0.24	1.36
20	double-pane green outer/clear inner, low-e on #2 surface, metal frame	6.88	0.49	0.62	0.58	3.29
21	double-pane high-performance tint outer/clear inner, metal thermal break frame	7.31	0.47	0.64	0.58	3.29

Simplifications Several simplifying assumptions were made in order to reduce the number of glazing constructions considered in the analysis. These assumptions were used in developing performance and cost data. All of these simplifications are believed to represent typical conditions for nonresidential buildings. They are summarized below:

- All glass is assumed to be $\frac{1}{4}$ inch thick. This thickness represents about 90% of glass sales for nonresidential buildings.
- Windows are assumed to all be 48 inches by 72 inches for both costing and performance calculations.
- Double glass is assumed to have a total thickness of 1 inch and is constructed of two $\frac{1}{4}$ -inch panes of glass.

Performance Characteristics The performance characteristics were calculated with a computer program (W&DG 1988). The algorithms in these programs are consistent with the methods recommended in the 1989 *ASHRAE Handbook—Fundamentals*. Both the shading coefficient and visible light transmission do not vary with frame type; window U-value, however, is influenced considerably by frame type.

Initial Costs Window costs are highly complex, since many window products are proprietary and have unique aesthetic properties. The factors that affect window costs include size and shape, heat treatment, glazing thickness, tinting, coatings applied to one or more surfaces of the glazing either in the manufacturing process or later in a

vacuum sputter machine, the type of frame, purchase volume, and many other factors. Costs are also affected by the type of wall in which the window is installed.

In order to manage the many fenestration constructions, the cost data were analyzed and reduced to a set of cost premiums that are additive. The data collected were analyzed marginally to identify the cost premiums for the glazing technologies of interest. For instance, the average premium for tinted glass (either bronze, gray, or green) was \$0.39/ft². The average premium for double glass (the addition of 1/4-inch clear glass as the inboard lite plus handling and fabrication cost) was \$3.02/ft². These cost premiums are considered additive and are listed in Table 5.

All the price quotes represent costs to the general contractor from a specialty contractor. A markup of 30% is added to all the cost premiums to account for the general contractor's overhead and profit and development costs. Information on the relative cost of fenestration systems was collected in a survey of glass installers, fabricators, and manufacturers.

RESULTS

The optimization results are presented from two perspectives. First, the cost-effectiveness boundaries between fenestration constructions are plotted as a function of climatic variables. The second perspective is presented as a plot of the optimal constructions as a function of WWR for a single climate.

Climate Boundaries

Figures 8 through 11 plot the cost-effectiveness boundaries between optimal fenestration constructions. Figures 8 and 9 present the results for the high-gain office building at window wall ratios of 15% and 45%. Figures 10 and 11 present the same information for the residential/hotel

TABLE 5
Incremental Costs for Fenestration Components,
Without 30% Markup (\$/ft²)

Premium For	Cost Premium (\$/ft ²)
Standard tint	0.39
High-performance tint	1.10
Medium performance reflective	1.68
High-performance reflective	1.81
Low-e	1.88
Double	3.02
Thermal break	1.50
Vinyl frame	4.00
Low-e coated mylar film	6.35

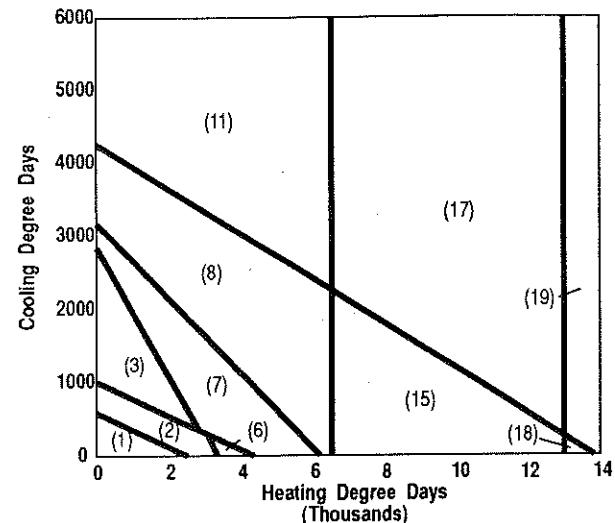


Figure 8 Cost-effectiveness boundaries between fenestration constructions based on CCD_{65} and HDD_{65} (numbers refer to Table 4), high-gain office, 3.5 W/ft^2 (38 W/m^2) lights and equipment, 1.5 W/ft^2 (16 W/m^2) lighting, WWR 15.

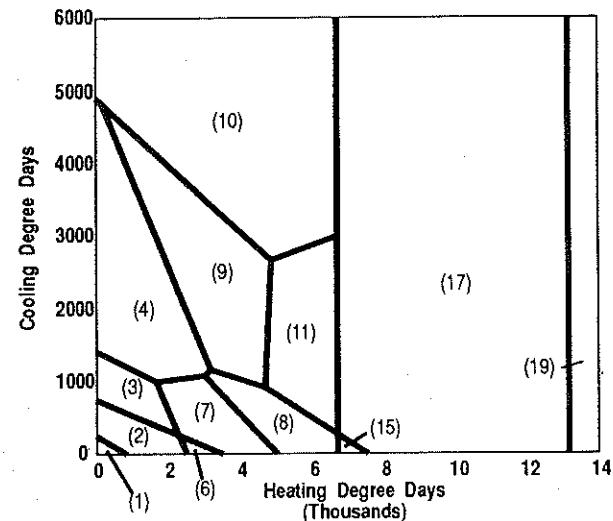


Figure 9 Cost-effectiveness boundaries between fenestration constructions based on CCD_{65} and HDD_{65} (numbers refer to Table 4), high-gain office, 3.5 W/ft^2 (38 W/m^2) lights and equipment, 1.5 W/ft^2 (16 W/m^2) lighting, WWR 45.

building. Both buildings are assumed to have the same lighting power (1.5 W/ft^2 of floor area and 50 fc illumination) in the daylighting savings calculation.

Each climate can be plotted as a point on the graphs. For example, St. Louis has an HDD_{65} of 4,860 and a CCD_{65} of 1,467. In the office building with a WWR of 15% (Figure 8), a U-value of 0.58 and shading coefficient of 0.39 would be optimal (#8, double glass with high-performance tint and low-e coating). At 45% WWR (Figure 9), the best choice would have a U-value of 0.48 and a

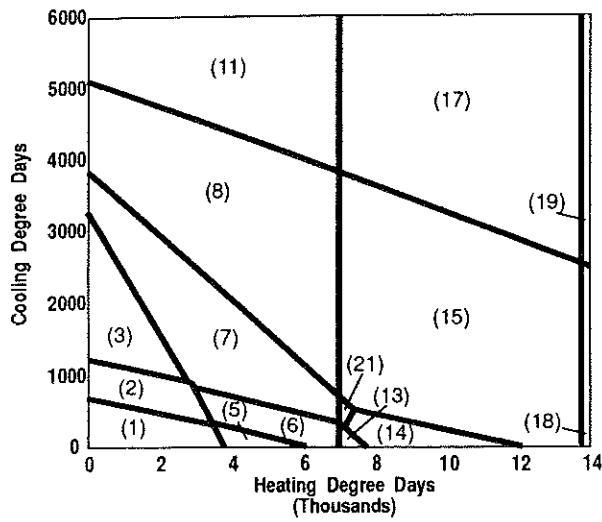


Figure 10 Cost-effectiveness boundaries between fenestration constructions based on CCD_{65} and HDD_{65} (numbers refer to Table 4), hotel, 1.65 W/ft^2 ($18 W/m^2$) lights and equipment, 1.5 W/ft^2 ($16 W/m^2$) lighting, WWR 15.

shading coefficient of 0.18 (#11, clear double glass with a reflective low-e mylar film).

For the residential building in St. Louis, the requirements would be slightly less stringent. At 15% WWR, the optimal window has a U-value of 0.71 and shading coefficient of 0.47 (#7, double glass with high-performance tint outer lite). At 45%, the top choice includes an additional low-e coating for a reduced U-value and shading coefficient of 0.58 and 0.39, respectively (#8).

In Figures 8 through 11, a vertical line represents a boundary between two fenestration constructions that vary only in U-value. For example, in Figure 8, the vertical line at 6,400 HDD_{65} is the boundary between plain metal frames and metal frames with a thermal break. Similarly, the vertical boundary at 13,000 HDD_{65} separates thermal break frames from vinyl frames. The sloping lines are boundaries primarily due to differences in shading coefficient and visible light transmittance.

Optimal Constructions for a Single Climate

Another perspective on the cost-effectiveness results is presented in Figure 12, using St. Louis as an example. The optimal fenestration constructions are plotted as a function of WWR for three different building occupancy types: (1) a RESidential occupancy with $1.2 W/ft^2$ of lighting power and a design illumination of 30 fc, (2) a LOW-gain commercial building with $1.25 W/ft^2$ of lighting power and a design illumination of 30 fc, and (3) a HIGH-gain commercial building with $2.0 W/ft^2$ of lighting power and a design illumination of 75 fc. The lighting systems are assumed to operate 2,700 hours a year with no daylighting contribution.

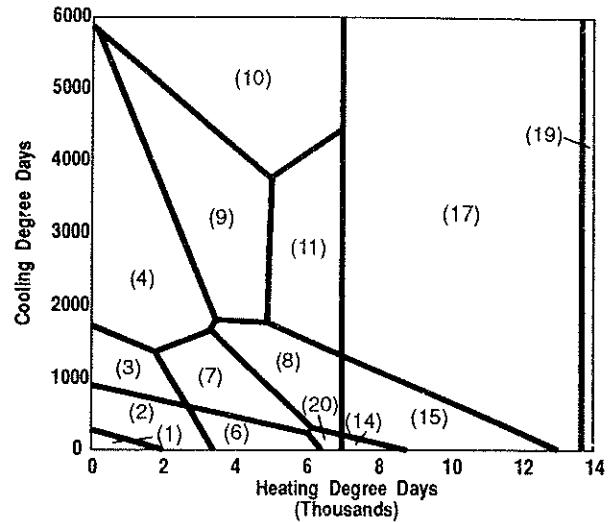


Figure 11 Cost-effectiveness boundaries between fenestration constructions based on CCD_{65} and HDD_{65} (numbers refer to Table 4), hotel, 1.65 W/ft^2 ($18 W/m^2$) lights and equipment, 1.5 W/ft^2 ($16 W/m^2$) lighting, WWR 45.

For each building type, the cost-effective fenestration construction is shown for each orientation and for a range of window wall ratios (see Table 4 for key to construction types). For instance, consider the high-gain commercial building. Up to about 35% WWR, the optimum glazing construction on the east, south, and west is a high-performance tinted glass with a low-e coating (#8). On the east and west, this fenestration construction is optimum until the window wall ratio is over 40%. After that, either clear double-pane glass with a suspended mylar film (#11) or double-pane reflective glass (#9) is the cost-effective choice. The optimum changes to double-pane clear glass with a mylar film (#11) at about a 35% WWR on the south. On the north side of the building, however, clear double-pane glass (#5) is optimum up to a WWR of about 16%. After that, green double glass (#6) is the cost-effective choice. The optimal choice for a uniform glass type on all orientations is double-pane high-performance tint with low-e (#8) up to a WWR of 30%; then the mylar film window (#11) becomes most cost-effective.

Sensitivity Analysis

This section discusses the effect of different sets of assumptions on the resulting criteria.

Internal Heat Gain The assumptions about internal gain affect the proposed criteria. The three buildings studied differed in their internal gains and use schedules.

In general, high internal loads will result in more stringent shading coefficient requirements. With higher internal gains, the cooling system operates a greater number of hours each year, and solar gains have a larger impact on

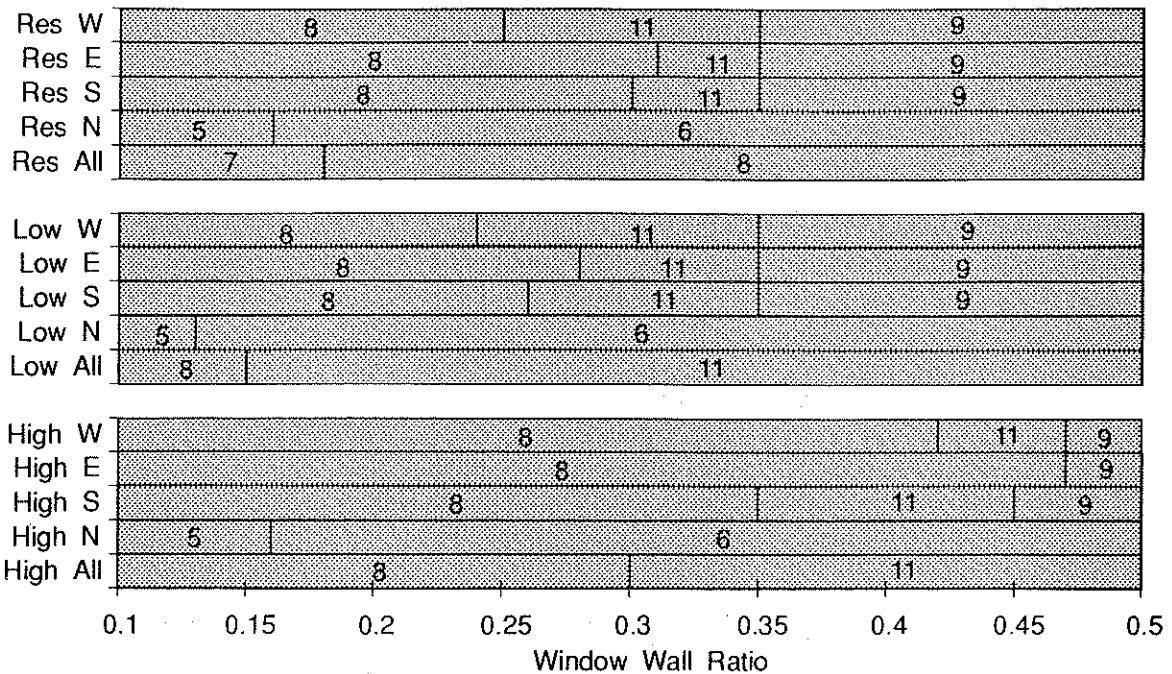


Figure 12 Optimal fenestration constructions for three building types in St. Louis, MO ($CDD_{65} = 1,467$, $HDD_{65} = 4,860$). Numbers correspond to fenestration constructions listed in Table 4.

total cooling energy. The climate boundaries in Figures 8 through 11 show that the same fenestration constructions become more cost-effective in slightly milder climates for the high-gain office building than for the hotel. In both cases, the lighting energy is assumed to be the same, and daylighting savings are identical. Therefore, the difference in shading coefficient criteria is due mostly to the difference in internal gains.

With high internal gains, the U-value requirements should be less stringent since less heating is necessary. However, shading coefficient and U-value are considered together in this analysis, and the high internal gain criteria turn out to be more stringent for both U-value and SC. The fact that the U-values are lower in the high internal gain criteria is due to the cost-effectiveness of low-emissivity coatings and mylar films used to decrease shading coefficients (while maintaining high visible light transmittance).

Daylighting The amount of daylighting savings considered in the life-cycle cost model affects the resulting criteria. Without consideration of daylighting, low-emissivity coatings would be replaced in many climates by reflective coatings as the optimal choice. The reflective coatings provide a lower shading coefficient at lower cost but have a much lower visible light transmittance.

The impact of daylighting savings is evident in Figure 12, where the WWR breakpoints between fenestration constructions are plotted for three buildings in St. Louis. In the graph, the shading coefficient criteria for each building become more stringent as WWR increases. However, the breakpoints for the residential and the low-gain commercial buildings occur at a lower WWR than in the high-gain

commercial building. Since the high gain building is assumed to use more lighting power (2.0 W/ft^2 [22 W/m^2] versus 1.2 W/ft^2 [13 W/m^2] in the residential building and 1.25 W/ft^2 [13 W/m^2] in the low-gain commercial building), it benefits more from glazing with a higher light transmission.

There are two benefits to considering daylighting savings in the criteria. First, it allows designs to be built that will accommodate future daylighting controls. Second, it accounts for the intangible benefit of occupant contact with the outside by giving it some weight in the economic optimization.

DISCUSSION

The life-cycle cost results show that cooling costs of commercial buildings vary greatly with fenestration performance, in particular shading coefficient. The shading coefficient, therefore, dominates the LCC results. Measures such as low-emissivity coatings, which can be considered U-value measures, are cost-effective due to their combination of shading and light-transmitting properties.

In general, the optimum fenestration construction changes to one with a lower shading coefficient (this usually means that the light transmission is also lower) as the window-wall ratio is increased. A lower light transmission will still achieve daylighting saturation at higher window wall ratios.

While it is not likely that automatic daylighting controls will be installed in all buildings, it may still be valid to assume daylighting controls for the following reasons:

- Even if daylighting controls are not installed when a building is initially constructed, tenants change in commercial buildings every five to six years, and there will be additional opportunities during the building's life to install daylighting controls and realize daylight savings. It makes good policy to design all buildings for some daylighting potential, even if it is not realized in the beginning.
- Crediting daylighting is a way to give weight to fenestration benefits that are difficult to quantify in monetary terms, including views, connection to the outdoors, and enhanced property values. If it were possible to quantify these intangible benefits, it is likely that the benefits would exhibit the same exponential decay as daylighting savings when window area or effective aperture is increased.

CONCLUSIONS

This research shows that if daylighting is not considered, the optimum fenestration construction for commercial buildings is generally the one with the lowest shading coefficient (usually high-performance reflective glass), thus reducing or eliminating daylighting potential. Accounting for energy savings from daylighting is a way to give value to the intangible benefits of windows, such as views and a sense of connection with the outdoors; it may even be reasonable to assume daylighting benefits if automatic controls are not initially installed.

The results of this methodology show fenestration features such as high-performance tinted glass and low-e coatings to be the lowest life-cycle cost option in many cases. Suspended mylar films are also found to be the

optimal choice under several conditions. Reflective glass, with low visible light transmittance, is found to be the best choice only in very warm climates or with large window areas in moderate climates.

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