Choosing the Optimum Fenestration in Commercial Buildings

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This paper presents a simple method of comparing the life-cycle cost of fenestration constructions in commercial buildings. The method is based on energy regression equations developed from DOE-2 computer simulations. The equations take account of window wall ratio (WWR), thermal transmittance (U-factor), shading coefficient (SC) and visible light transmission (Tvis). Coefficients are developed for high internal gain commercial buildings, low internal gain commercial buildings and continuously operated residential buildings or hotels. Climate variables are heating and cooling degree days at base 65°F (18.3°F). Fenestration options can be evaluated for the whole building (assuming uniform fenestration distribution) or separately for each of the major orientations.

The energy models consider daylighting benefits associated with fenestration. Required inputs are lighting power density and design illumination in the perimeter zones of the building. The daylighting equation can also be used to give weight to the intangible benefits of fenestration, such as views, connections with the out-of-doors, and enhanced property value.

The energy use results from the regression equations are integrated with simple economic models so that the life-cycle cost of fenestration constructions can be easily compared. The cost effective fenestration choice for several climates and building conditions is presented to illustrate the use of the model.

Introduction

The choice of fenestration in commercial buildings is often driven by code requirements or by initial construction costs. If energy costs were considered in the selection of glazing, alternative choices might result in significant energy savings. However, accurate energy cost data are not readily available and generally require time-consuming computer simulations prepared by skilled professionals.

This paper presents a simple procedure for comparing fenestration options. It takes account of window area, lighting power, desired illumination and building occupancy patterns. When these factors are known, simple equations may be used to evaluate competing fenestration options. For each fenestration option under consideration, it is necessary to know the thermal transmittance (U-factor), the shading coefficient (SC), the visible light transmission (T_{vis}) and the incremental initial cost. It is not necessary to know the absolute initial construction cost of each option, but only the relative cost (the difference between the fenestration options). The result of the procedure is ranking of glazing alternatives based on relative life-cycle cost.

Methodology

Life-cycle cost is used to select the optimum fenestration construction. The life-cycle cost methodology and the associated energy equations are presented in this section.

Life-Cycle Cost

For a given set of climate conditions, the optimum fenestration construction is the one 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 fenestration construction is calculated with Equation (1).

$$LCC_i = COST_i \cdot WWR + PV_e \cdot kWh_i + PV_g \cdot Therms_i \qquad (1)$$

where

LCC_i = Relative life-cycle cost of the ith fenestration construction per square foot of wall area ($\$/ft^2$).

$COST_i$ = The construction cost of the ith fenestration construction per square foot of glass ($\$/ft^2$).

WWR = Window wall ratio (unitless).

PV_e = The present value of a kilowatt-hour per year of electricity used over the life of the building (\$/kWh).

kWh_i = The annual electricity use of the building with the ith fenestration construction per square foot of wall area. See Equation (3). (kWh/ft^2).

PV_g = The present value of a therm of natural gas used each year over the life of the building (\$/kWh).

$Therms_i$ = The annual gas use of the building with the ith fenestration construction per square foot of wall area. See Equation (2). (therms/ft^2).

The present value terms, PV_e and PV_g, used in the results section of this paper are \$0.96/kWh and \$6.72/therm. These represent energy costs of \$0.08/kWh and \$0.56/therm along with a real discount rate of 3% (without inflation) and building life of 15 years. Other values may easily be substituted into the equation[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)). These equations are shown below.

$$Therms_i = h_o + h_1 * HDD_{65} + h_2 * WWR * HDD_{65} * U_i + h_3 * WWR * HDD_{65} * SC_i \quad (2)$$

$$kWh_i = c_o + c_1 * HDD_{65} + c_2 * CDD_{65} + c_3 * WWR * HDD_{65} * SC_i + c_4 * WWR * CDD_{65} * SC_i + kWh_{lght} \quad (3)$$

where

WWR = Window wall ratio (unitless).

U_i = The U-value of the ith fenestration construction (Btu/(h·ft^2°F)).

SC_i = The shading coefficient of the ith fenestration construction (unitless).

HDD_{65} = Heating degree days at base 65°F (18.3°C) for a particular climate zone.

CDD_{65} = Cooling degree days at base 65°F (18.3°C) for a particular climate zone.

kWh_{lght} = Lighting energy in the perimeter zone. Discussed in the next section.

c_n, h_n = Coefficients determined through regression analysis.

In comparing fenestration constructions in a given climate, the coefficients h_0, h_1, c_0, c_1 and c_2 are not significant because the associated terms cancel each other when two or more fenestration constructions are compared. Only the significant coefficients (h_2, h_3, c_3 and c_4) 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/ft^2 (38 W/m^2) total lighting and equipment load, a low gain commercial building with 1.75 W/ft^2 (19 W/m^2), and a residential type occupancy with 1.65 W/ft^2 (18 W/m^2) which is continuously operated. Both the high and low gain commercial buildings are assumed to be operated about 12 hours per day Monday through Friday and a half a day on Saturday.

The energy use coefficients are calculated through regression analysis of DOE2.1D computer simulation results. The building model used for these runs is a simple five-zone building shown in Figure 1. 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 Btu/(h·ft^2°F) (6.76 W/(m^2°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.

While the building envelope and the HVAC system represent a single building configuration, the results of this analysis should be useful to analyze fenestration choices in a wide range of building types. This life-cycle cost methodology produces a ranking of fenestration constructions based on relative cost-effectiveness. The

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

impact of specific HVAC system and envelope characteristics on the relative ranking is much smaller than on the absolute energy consumption of a specific building.

Figures 2 and 3 compare the results of Equations (2) and (3) 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 the DOE-2 results. The plots are presented for the low gain commercial building, however, the graphs are very similar for each of the three building types. 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 between 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 accounted for in the simplified energy model. 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).

$$kWh_{lght} = \frac{P_L * H_L (1 - K_d)}{1000} \quad (4)$$

where

kWh_{lght} = Annual electricity used for lighting in the perimeter zone per square foot of wall area $(kWh/(y \cdot ft^2))$.

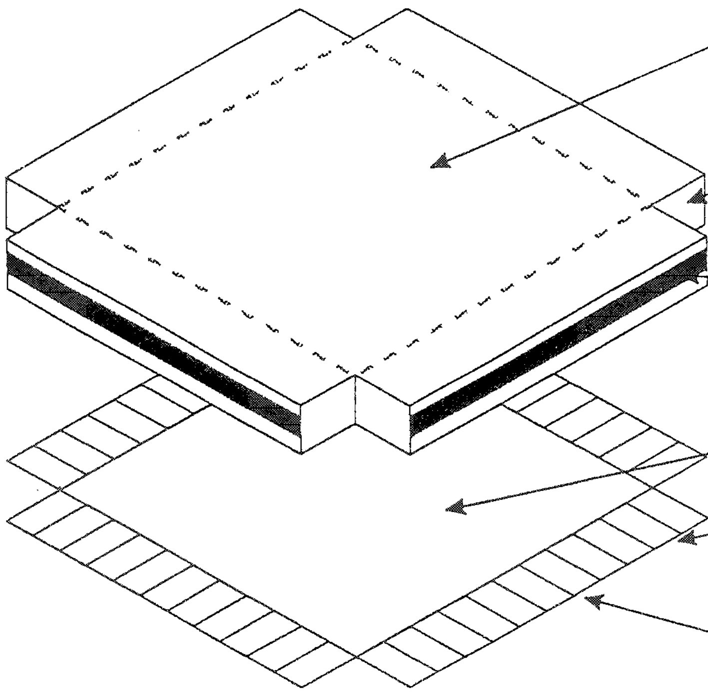

Figure 1. Five Zone Computer Model Used in DOE-2 Analysis

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	Winnemuca, 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

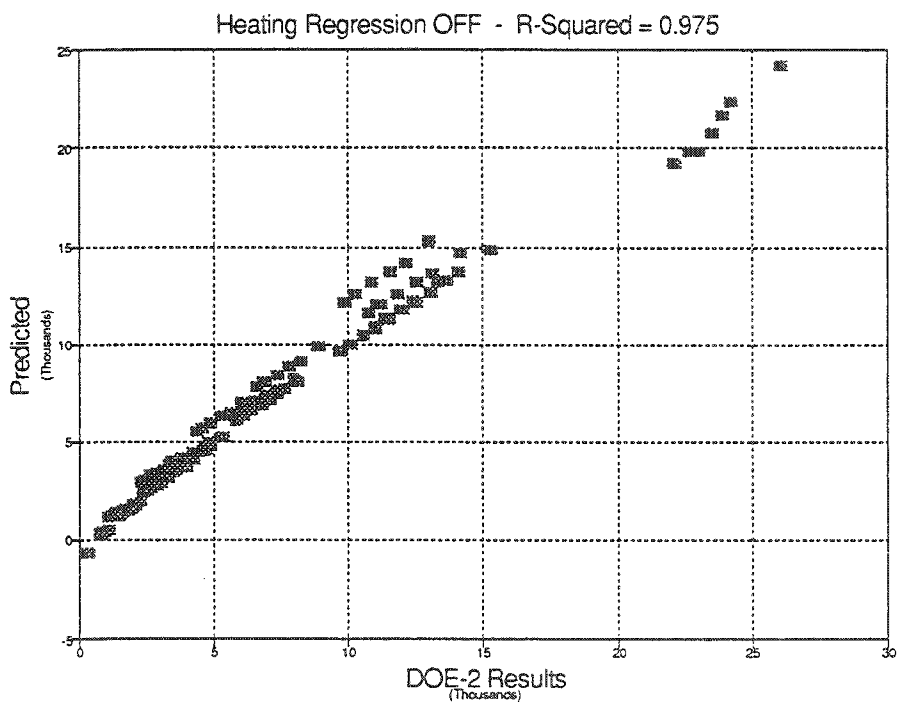

Figure 2. Heating Regression Results for High-Gain Commercial Building. Compares predicted results using Equation (2) to DOE-2 simulation results. Units in thousands of therms of natural gas.

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 controls (h/yr).
K_d = Daylight savings fraction from Equation (5) (unitless).

With continuous dimming daylighting controls, the daylight savings fraction in a perimeter space can be expressed 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:

$$K_d = [\phi_1 + \phi_2 \, (C/T_{vis_i})] \; x \; [1 - e^{(\phi_3 + \phi_4 \cdot C) WWR \cdot T_{vis_i}}] \qquad (5)$$

where

T_{vis_i} = Visible light transmission of the ith fenestration construction (unitless).
WWR = Window wall ratio (unitless).
C = Design Illumination (footcandles).
ϕ_n = Coefficients listed in Table 3. From (Sullivan 1988).

The coefficients for the daylighting equation 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 climate 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.

Results

When the lighting power and illumination levels are known (or when reasonable assumptions can be made), the model can be used to evaluate fenestration options and to find the optimal construction at different window wall

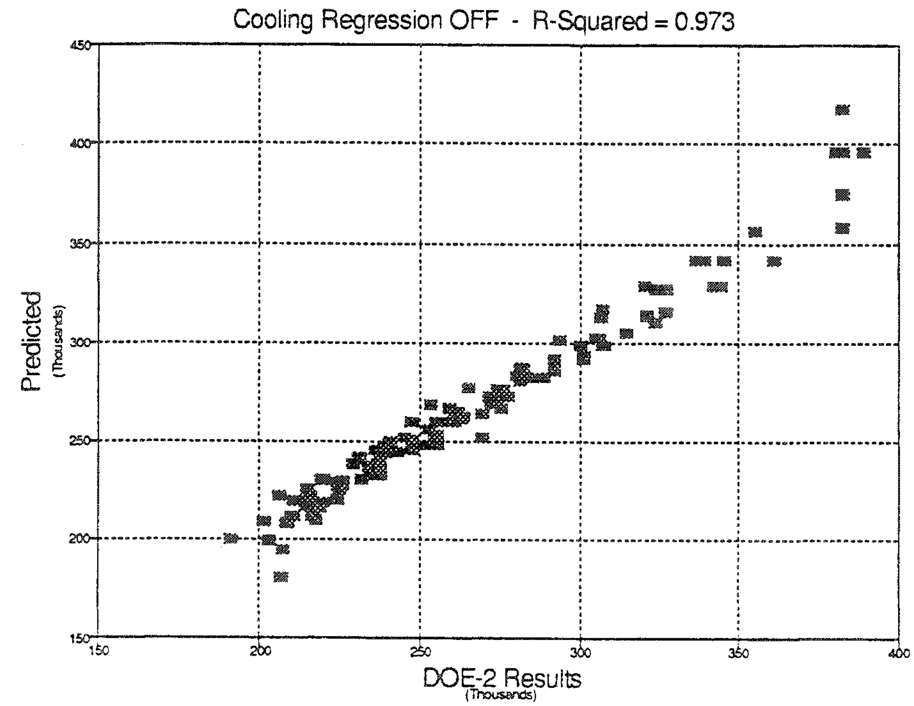

Figure 3. Cooling Regression Results for High-Gain Commercial Building. Compares predicted results using Equation (3) DOE-2 simulation results. Units in thousands of kWh of electricity.

Table 3. Daylighting Coefficients for Equation (5)

	Values Used in the Analysis	Madison	Lake Charles
ϕ_1	.737	.737	.737
ϕ_2	-.000317	-.000317	-.000263
ϕ_3	-24.71	-20.818	-27.521
ϕ_4	.234	.201	.266

ratios. Results of the analysis can be presented in severalways; one is to show the cost effective glazing choice for each window wall ratio. This is illustrated in Figures 4 through 8 for several climates.

Table 4 shows a subset of the fenestration constructions considered in the optimization. Only those constructions that are optimal for one or more of the conditions described in Figures 4 through 8 are included. Table 4 gives the performance characteristics of the optimal glazing constructions and the relative cost. All costs are relative to single clear glass in a metal frame which is assumed to have a cost of zero. The costs are based on a survey of glazing contractors and include a 30% general contractor markup. The U-factor, shading coefficient and visible light transmittance for each of the fenestration constructions is calculated using the Window 3.1 program (W&DG 1988).

A total of 104 fenestration constructions were considered in the life-cycle cost analysis, and they include combinations of the following: (1) standard metal framing, metal framing with a thermal break and vinyl frames, (2) single and double glass, (3) clear, bronze, green and high performance tinted glass for the outer lite, (4) clear, green and high performance tinted glass for the inner lite, (5) low-emissivity coating on the second surface, the third surface or both, (6) low-emissivity coated mylar film suspended between double panes of clear glass and (7) medium and high performance reflective coatings on the second surface.

Table 4. Fenestration Construction Reference for Figures 4 through 8

Number	Construction	Cost	SC	Tvis	U-Value
1	single pane clear, metal frame	0.00	0.95	0.88	1.21
2	single pane green tint, metal frame	0.51	0.71	0.75	1.21
3	single pane high performance tint, metal frame	1.43	0.61	0.72	1.21
4	single pane high performance reflective coating, metal frame	2.86	0.25	0.07	1.01
5	double pane clear, metal frame	3.93	0.81	0.78	0.71
6	double pane green outer/clear inner, metal frame	4.43	0.57	0.66	0.71
7	double pane high performance tint outer/clear inner, metal frame	5.36	0.47	0.64	0.71
8	double pane high performance tint outer/clear inner, low-e on #2 surface, metal frame	7.80	0.39	0.59	0.58
9	double pane green outer/clear inner, high perf. reflective coating on #2 surface, metal frame	6.79	0.18	0.06	0.64
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
11	double pane clear with suspended mylar film, metal frame	12.18	0.18	0.25	0.48
12	double pane clear, metal thermal break frame	5.88	0.81	0.78	0.58
13	double pane greenouter/celar inner, metal thermal break frame	6.38	0.57	0.66	0.58
14	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
15	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
16	double pane clear with suspended mylar film, metal thermal break frame	14.13	0.18	0.25	0.35
17	double pane green outer/clear inner, low-e on #2 surface, metal thermal break frame	8.83	0.49	0.62	0.45

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 include: (1) all glass is assumed to be 1/4 inch thick, (2) windows are assumed to all be 48 inches by 72 inches for both costing and performance calculations and (3) double glass is assumed to have a total thickness of one inch and is constructed of two 1/4 inch panes of glass.

Figures 4 through 8 each show three building 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 1.2 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 per year with no daylighting contribution.

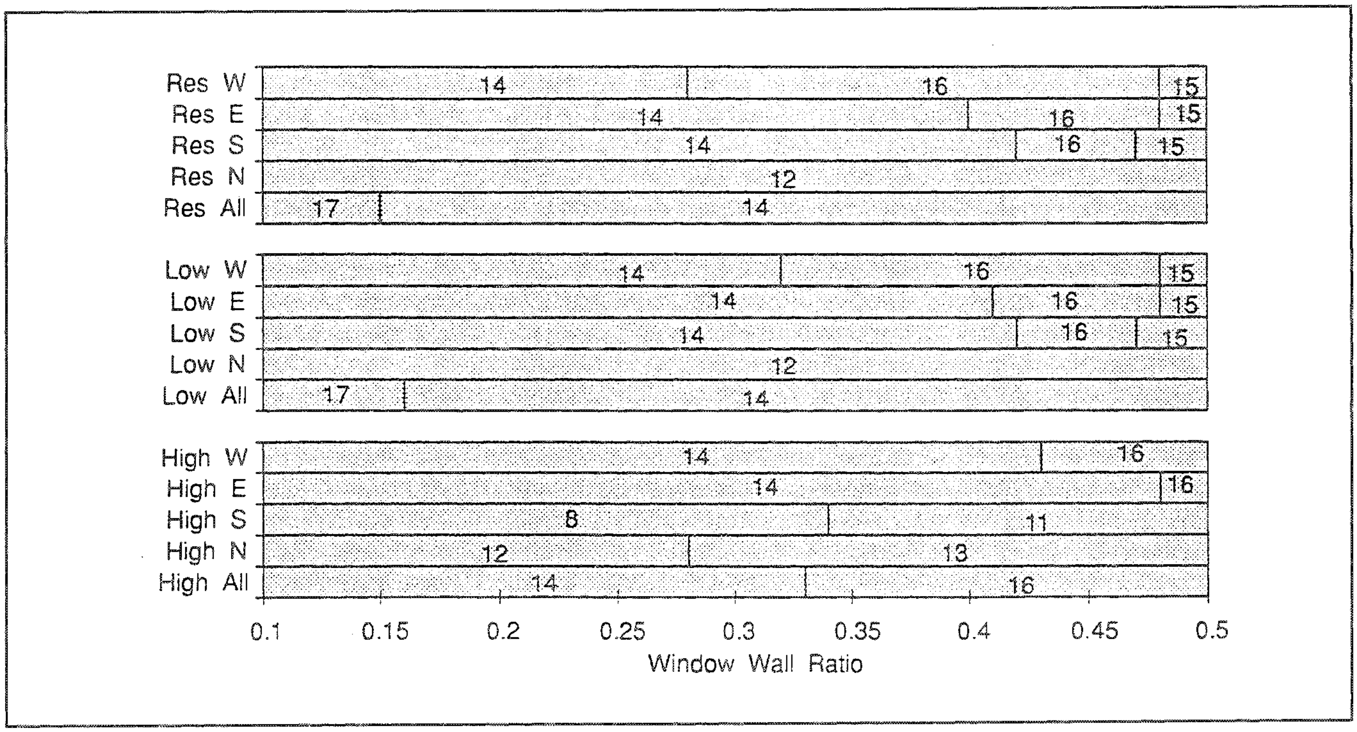

Figure 4. Optimal Fenestration Constructions for Madison, WI (CDD_{65} = 542, HDD_{65} = 7466). Numbers correspond to fenestration constructions listed in Table 4.

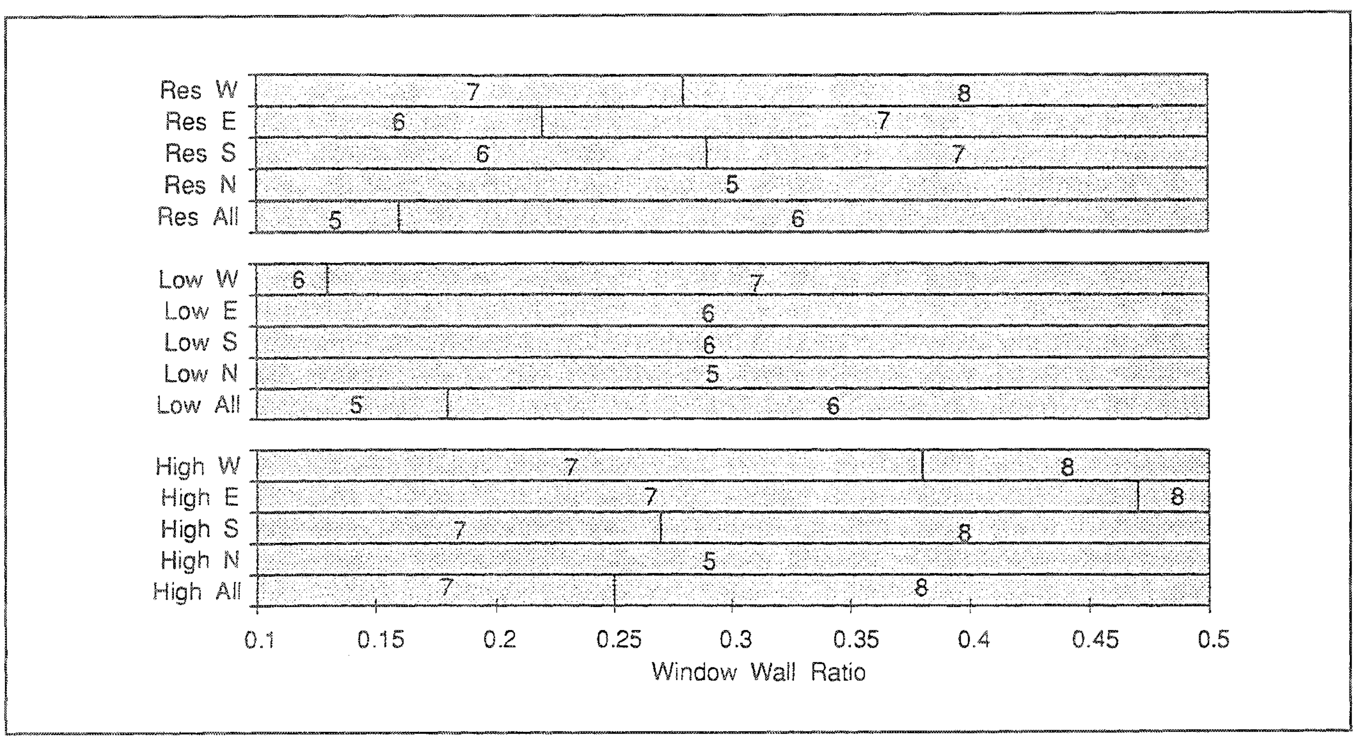

Figure 5. Optimal Fenestration Constructions for Seattle, WA (CDD_{65} = 106, HDD_{65} = 5281). Numbers correspond to fenestration constructions listed in Table 4.

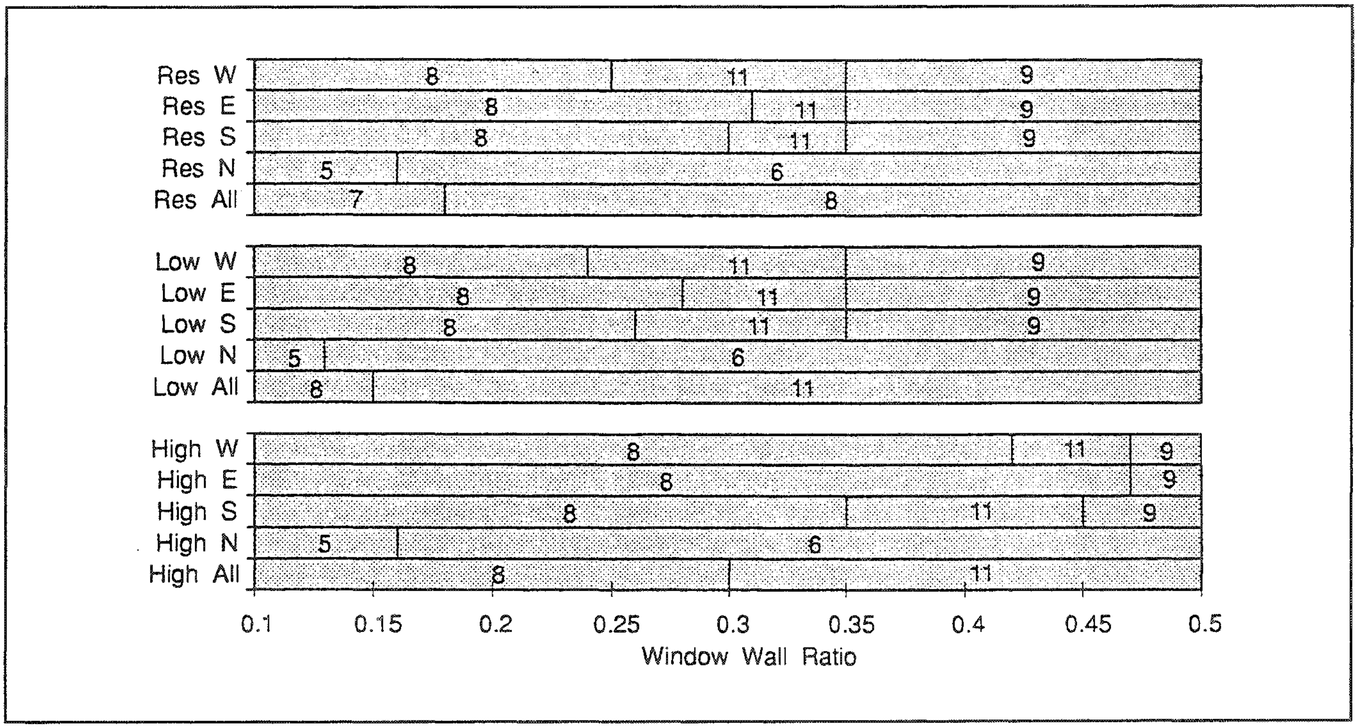

Figure 6. Optimal Fenestration Constructions for St. Louis, MO (CDD_{65} = 1467, HDD_{65} = 4860). Numbers correspond to fenestration constructions listed in Table 4.

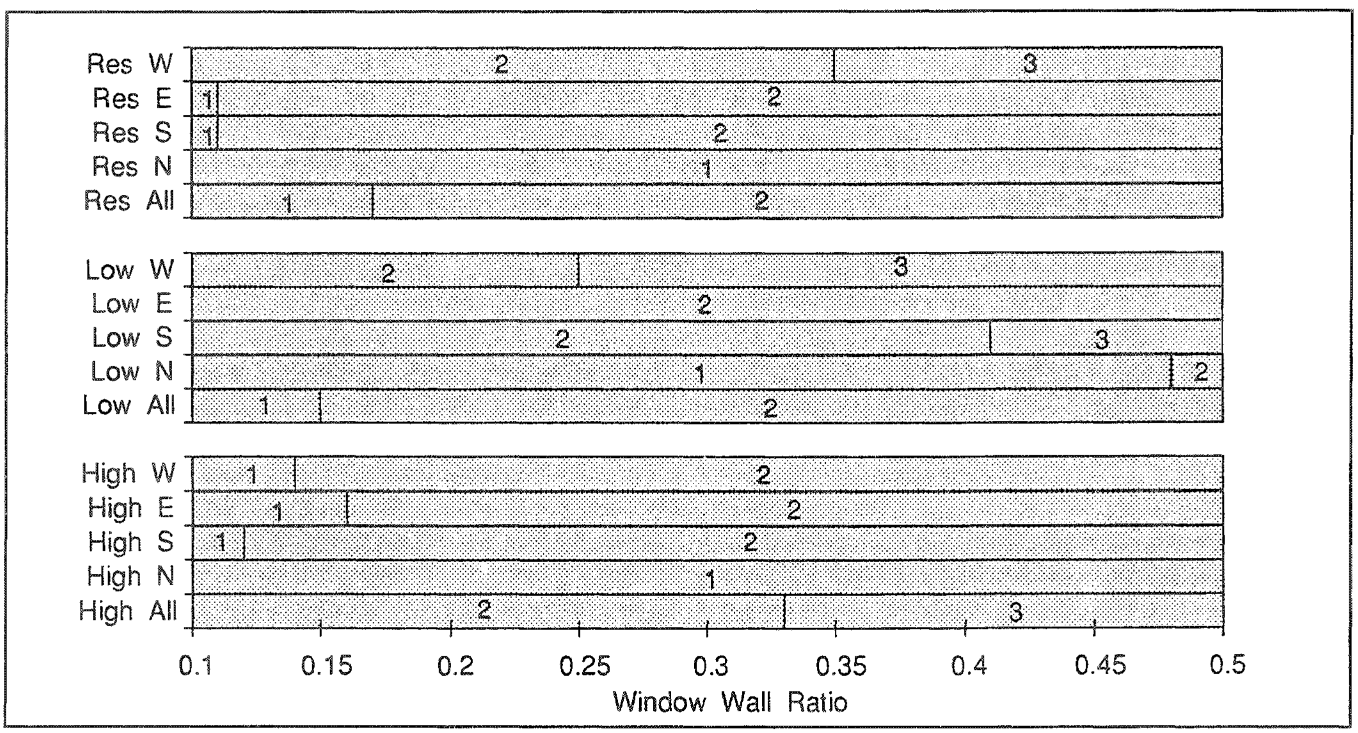

Figure 7. Optimal Fenestration Constructions for Los Angeles, CA (CDD_{65} = 472, HDD_{65} = 1494). Numbers correspond to fenestration constructions listed in Table 4.

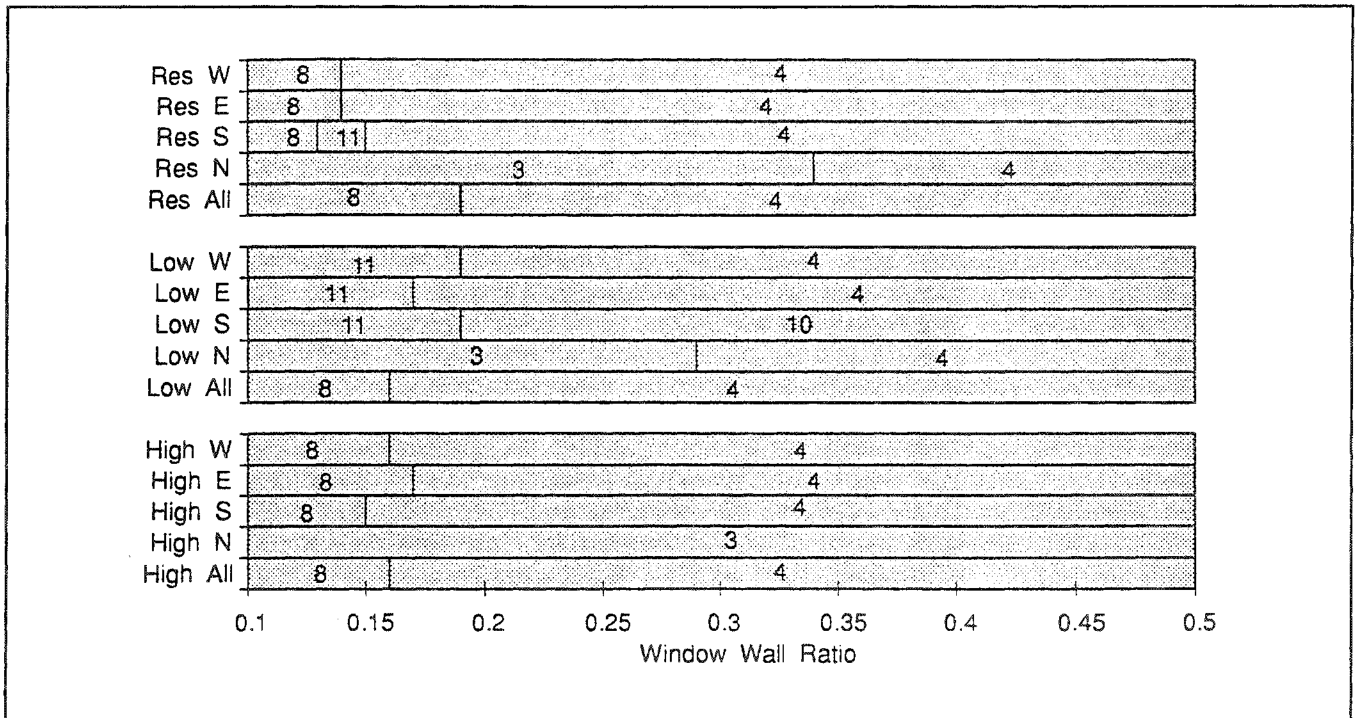

Figure 8. Optimal Fenestration Constructions for Miami, FL (CDD_{65} = 4045, HDD_{65} = 185). Numbers correspond to fenestration constructions listed in Table 4.

For each building type, the cost effective fenestration construction is shown for each orientation and for a range of window wall ratios. For instance, consider the high gain commercial building in Madison (Figure 4). The optimum glazing construction on the east, south and west is a high performance tinted glass with a low-e coating (#8 and #14). A thermal break frame is cost effective on the east and west but not the south. On the east and west, this fenestration construction is optimum up to a window wall ratio of about 45%. After that, clear double glass with a suspended mylar film (#16) is the cost effective choice. The cost effective choice changes to double clear with a mylar film (#11) at about a 35% WWR on the south. On the north side of the high gain commercial building, however, clear double glass (#12) is optimum up to a WWR of about 28%. After that, green double glass (#13) is the cost effective choice. A thermal break frame is cost effective on the north for all constructions. The optimal choice for a uniform glazing on all orientations is the high performance tinted glass with a low-e coating (#14) up to a WWR of 33%, then clear double glass with a suspended mylar film (#16) is the optimal choice. Thermal break frames are cost-effective in both cases.

Discussion

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.

(1) Even if daylighting controls are not installed when the building is initially constructed, tenants change in commercial buildings every five to six years and there will be additional opportunities during the building 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.

(2) Crediting daylighting is a way to give weight to fenestration benefits that are difficult to quantify in monetary terms, including views, connection to the out-of-doors 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. (Effective aperture is defined as the product of window wall ratio, WWR, and visible light transmittance, T_{vis}.)

It is not the intent of this paper to show that providing an effective aperture of a certain size will assure successful daylighting. While effective aperture is important, the success of daylighting also depends on a number of other factors such as ceiling height, surface reflectances within the room, brightness contrast and glare and the layout of work stations and/or tasks within the space.

The architect must weigh many considerations when selecting a glazing material, and energy performance is only one. Another important consideration is color and reflectivity. Fenestration materials with a low visible transmittance or with a high exterior reflectivity provide a more uniform exterior appearance to the building. It is not as easy to see inside where there can be a variety of interior designs or even window treatments (draperies in one place, blinds in another). While a uniform exterior appearance may be desirable to some, a visually open facade may be desirable to others. For instance, windows with a high light transmission (generally clear glass) are highly desirable for ground level retail shops so that passers by can see the merchandise on display. Some communities such as San Francisco have planning policies that encourage high transmission glass so that building facades do not appear so opaque (the opposite of providing a uniform appearance).

Conclusion

This research shows that if daylighting is not considered, the optimum fenestration construction 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 out-of-doors; therefore, it may be reasonable to assume daylighting benefits even 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.

Acknowledgments

This research was conducted by Eley Associates for the Primary Glass Manufacturers Council (PGMC) and the American Architectural Manufacturers Association (AAMA). Valuable assistance and data was provided by the PGMC Management Committee and the PGMC Technical Committee.

Endnotes

1. This 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 sake of simplicity, and their impact on the relative ranking of fenestration constructions could be a subject for further study.

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