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ABSTRACT - The development of a simplified algebraic expression that can be used to predict the effects of various window parameters on residential energy use is documented. A comprehensive parametric study of a prototypical single-family ranch-style house was performed using the DOE-2.1B energy analysis simulation program. The data base generated for the study consisted of the heating, cooling, and total energy requirements and subsequent costs due to changes in the fenestration characteristics of orientation, size, conductance, and shading coefficient. Incremental effects due to shade management, night insulation, and overhangs were also part of the data base. Climate sensitivity was established by considering results from four geographic locations representative of the climate extremes in the continental U.S. Multiple regression techniques were used to generate a simplified algebraic expression that relates energy use to the parameters varied. This representation could form the basis for a simplified design tool for selecting optimal fenestration parameters

INTRODUCTION

Window performance analysis has become in recent years a major concern in defining the overall energy use patterns of most types of buildings. Of particular importance among builders and designers in both the residential and commercial sectors are the interactions and tradeoffs among the various configuration parameters that define a structure. Windows represent a primary focus of study because they influence the thermal environment of a building through convective and conductive heat transfer, radiant transfer, and mass transfer. Research in new window systems has concerned itself with changes to one or more of these properties. The introduction of double- and triple-pane glazing is an example in which both the conductive and radiant characteristics are affected. Low emissivity coatings are also being used to reduce the radiative component of the thermal losses while maintaining a high solar transmission. Control of optical and thermal characteristics and mass transfer (infiltration/air leakage) can be provided by insulating shutters and/or movable insulation.

Systems such as these have added to the complexity of analyzing window performance. A principal area of investigation being carried on by the Windows and Daylighting Group of the Applied Science Division at Lawrence Berkeley Laboratory has been the development of alternative analytical tools from which building designers and architects can conveniently study the effects of window systems on building energy performance and costs. The work reported in this paper describes an approach that uses results from numerous building energy simulations with the DOE-2.1B computer program (1) to develop an algebraic expression that accurately predicts residential energy use.

A prototypical single-family ranch-style house was selected for analysis. The building configuration modeled was a single-story, 16.67 m (55 ft) by 8.53 m (28 ft), one-zone structure of wood frame construction with window sizes fixed on three sides at 15% of the wall area (Fig. 1). The size of the fourth or primary side provided the parametric variation on window size which varied from 0% to 60% of the wall area (0% to 17.1% floor area). Single, double, triple, and high-resistive glazing (U=0.534 W/m^2 ^{o}C, 0.1 Btu/hr-ft^2 ^{o}F) as well as shading coefficient values of 0.4, 0.7, and 1.0 served as the glazing property parametrics. Results were obtained for eight orientations covering a complete 360^o rotation in 45^o increments. More details of the thermal and operational characteristics of the prototype are provided in an earlier report (2).

Incremental changes to the glazing properties due to night insulation, shade management, and overhangs were also investigated. Insulation levels of R=5.68 m^2 ^{o}C/W (1.0 hr-ft^2 ^{o}F/Btu), 14.2 (2.5), and 28.4 (5.0) were implemented at night during the months of October to May. Shade management was simulated by deploying a shade that reduced solar heat gain by 40% if the direct solar gain on a particular window exceeded 63 W/m^2 (20 Btu/ft^2). Overhangs were modeled using a fixed width of 0.76 m (2.5 ft) above each window.

Two standard year (WYEC) weather profiles (3) were used in the analysis, Madison, Wisc., and Lake Charles, La. Their selection was based on the expectedly large thermal load that can be expected differences due to their geographic locations. Simulation runs were also made for configurations located in Washington, D.C., and Phoenix, Ariz., although fewer runs were made than for the two primary locations. The purpose of investigating these additional climates was to verify the existence of a very convenient proportional relationship, reported in a recent paper (4), between building thermal loads for varying configuration parameters. The relationship was shown to be independent of climate location and to cover a broad spectrum of those variables that influence a building's energy use.

DISCUSSION

The data base generated by the DOE-2.1B simulations was used to develop a simplified algebraic expression to predict energy use and cost for the model. This was accomplished through multiple regression procedures using the method of least squares to define the best fit to the data sets. Sets of independent variables (configuration parameters) were defined from which dependent variables (heating and cooling energy) were predicted. The general form of the equation consisted of the explicit definition of the conductive and solar radiation effects of the fenestration system as follows:

$$\Delta E = \beta_1(k_n U_g A_g) + \beta_2(\Sigma k_{no} U_{go} A_{go}) \quad \text{conductance} \qquad (1)$$

$$+ \beta_3(k_o k_s SC_g A_g)^2 + \beta_4(k_o k_s SC_g A_g) \quad \text{solar}$$

$$+\beta_5(\Sigma k_{oo} k_{so} SC_{go} A_{go})$$

where

- β = regression coefficients
- U_g = primary glazing U-value ($W/m^2\,^oC$)
- A_g = primary glazing area (m^2)
- SC_g = primary glazing shading coefficient
- U_{go} = off-primary glazing U-value ($W/m^2\,^oC$)
- A_{go} = off-primary glazing area (m^2)
- SC_{go} = off-primary shading coefficient
- k_n = primary glazing night insulation factor
- k_o = primary glazing overhang factor
- k_s = primary glazing shade management factor
- k_{no} = off-primary glazing night insulation factor
- k_{oo} = off-primary glazing overhang factor
- k_{so} = off-primary glazing shade management factor

The ΔE term represents the annual heating and cooling energy effect of the fenestration, with the total space conditioning being determined by the sum of the two. Figure 2 shows the heating energy regression coefficients for Madison. The relative importance of each term on energy use can be ascertained from such a figure and others related to cooling energy and total energy. For example, Madison is dominated by the heating coefficients (both conductance and solar terms); whereas the cooling energy solar gain coefficients dominate in Lake Charles. The glass conductance effect on cooling energy is minimal in both locations. The sign difference between the conductance (β_1) and solar (β_4) terms in the heating energy coefficients indicates the capability of trading off the two window properties. However, this is apparent in geographic locations with moderate to harsh winters; it is of course not true in climates dominated by cooling requirements.

The regression fits to the data sets were very good. The squared multiple correlation coefficient, r^2, the proportion of variation explained by the independent variables, was on the order of 0.99 for all locations. A value of 1.0 would mean perfect correlation, i.e., that all variation in the dependent variable could be explained by variations in the independent variables. The standard error of the estimate, which can be interpreted as the standard deviation of the residuals, (the difference between actual and predicted values) was the highest for cooling in Madison, about 4%. This resulted from the low cooling energy required, implying that a small deviation is more significant.

The form of equation (1) permits a calculation of the window size that minimizes energy use or cost. Taking the derivative with respect to the primary window area and equating the result to zero yields:

$$A_g = [-\beta'_4 - \beta'_1 * (U_g/SC)]/(2.*\beta'_3 * SC) \qquad (2)$$

where the prime on the coefficients indicates the summed heating and cooling values, i.e., $\beta'_1 = \beta_{1c} k_{nc} + \beta_{1h} k_{nh}$. Areas are definable for:

$$U_g/SC < \beta'_4/\beta'_1 \qquad (3)$$

The minimum energy cost solution is found by modifying the energy equation to account for the unit costs of gas and electricity. Using \$.60/therm (\$6.00/Mbtu, \$5.69/GJ) for gas and \$.07/kwh (\$20.50/Mbtu, \$19.43/GJ) for electricity, the regression coefficients become, with SI units (using β_1 as an example):

$$\beta'_1 = 19.43\ \beta_{1c} k_{nc} + 5.69\ \beta_{1h} k_{nh} \qquad (4)$$

Figures 3, 4, and 5 illustrate different aspects of results derived from the above expressions. Figure 3 shows solutions for the optimum primary window area facing south in Madison for various configuration parameters and different electricity and gas cost ratios. It is apparent that the reduction in optimum area is associated with increased electricity cost (cooling) and/or reduced gas cost (heating), denoted by the progression from curve A through D. The use of night insulation has a dramatic effect on all the curves which results from the high heating requirements in Madison. Note, however, that these results do not indicate if the energy-saving or cost-minimizing solution is a cost-effective solution.

Figure 4 presents the net annual useful flux (the solar gain which contributes to a reduction in heating load) in Madison for a south-facing primary window area of 6.13 m^2 (66 ft^2). These data were obtained from a solution to equation (1) by considering only the heating energy requirement. Also shown on the figure are conductance and shading coefficient values representative of current glazing products. This type of presentation allows a quick evolution of the winter performance of various fenestration systems in which U-value and shading coefficient can be independently varied.

The effect of climate on heating energy can be ascertained by observing Fig. 5 which shows the proportional nature of the relationship between different window configurations. Similar linearities are also present for other configurational parameters such as wall, roof, and floor insulation and mass properties, infiltration levels, etc., discussed in an earlier paper (4). Understanding building performance is greatly simplified through definition of a procedure utilizing this relationship. Incremental thermal load and energy results can be obtained for any location for an alternate configuration, provided the performance of a base-case configuration has been defined.

CONCLUSIONS

This paper has discussed results of a study whose objective was the development of a simplified analytical procedure for analyzing the effects of fenestration on residential energy use. The work was undertaken as a parametric study covering a range of window properties: orientation, size, conductance, and shading coefficient. The intent was to bracket each variable so that current and/or future glazing characteristics could be conveniently analyzed. Several conclusions can be ascertained from the work:

a. Results indicate the feasibility of using regression-derived equations to accurately predict energy use as a function of the above window properties.

b. The regression solution indicates that the components that contribute to a building's energy use are independent of each other within the range of parameters investigated.

c. The use of precalculated regression coefficients with a simple energy or cost equation suggests that several easily used but powerful fenestration design tools could be developed. Unlike many other simplified design tools based on simple calculation procedures, these results are based on use of a sophisticated hour-by-hour simulation tool that properly accounts for complex thermal effects in a residence.

d. Development of a simplified design tool could include selection of optimal fenestration parameters and cost/benefit comparisons among alternative products and designs. The procedure described could be used within the context of a sophisticated microcomputer design tool using user friendly input/output or, because of the algebraic nature of the regression equation, the tool could be programmed into a small desk-top calculator.

e. Climatic effects can be accounted for by establishing the variation of a base case design for all locations of interest and determining the linear relationship between the base case and whatever alternate configurations are desired.

f. Aside from the simplified tool capabilities resulting from the regression equation, the regression coefficients give insight into the window performance associated with specific geographic locations. For example, in Madison, the energy reduction caused by increased solar gain is apparent in the negative sign attached to the solar radiation regression coefficient; in Lake Charles, the signs of all coefficients are positive.

REFERENCES

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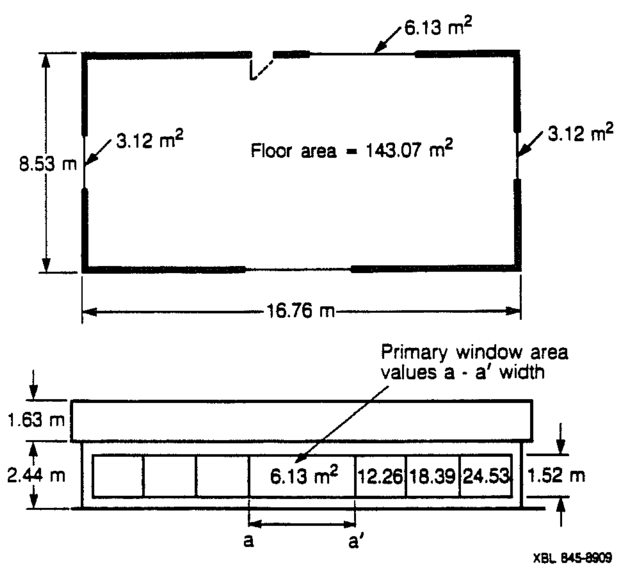


Fig. 1. Residential model description.

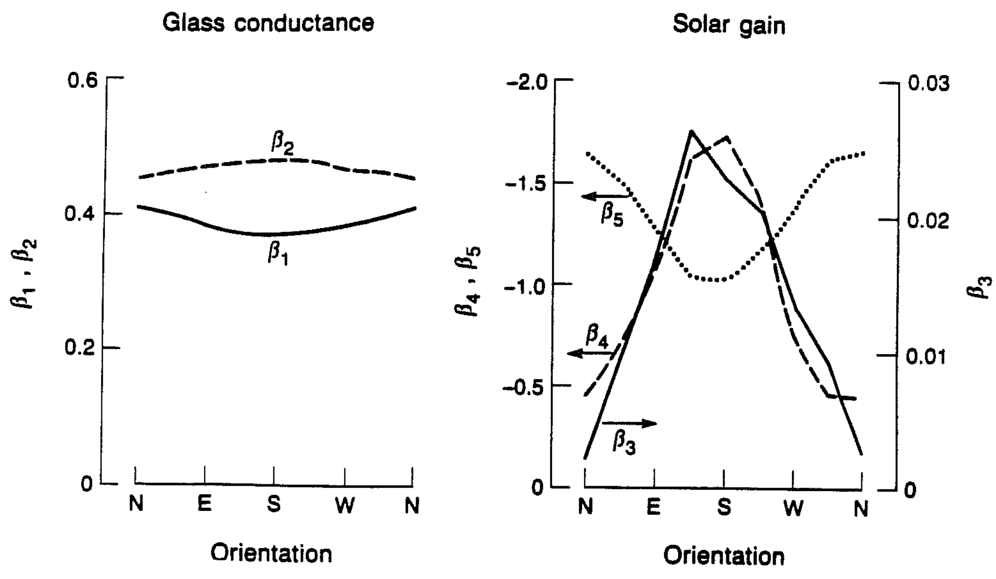


Fig. 2. Residential heating energy regression coefficients for Madison, Wisc., as a function of primary window orientation.

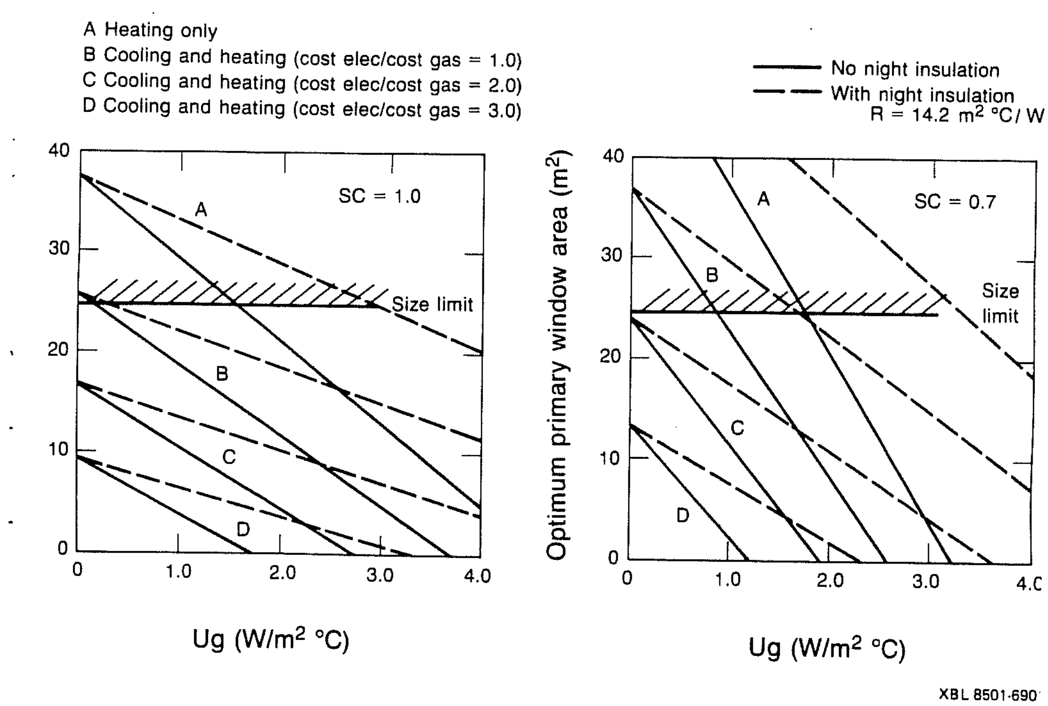
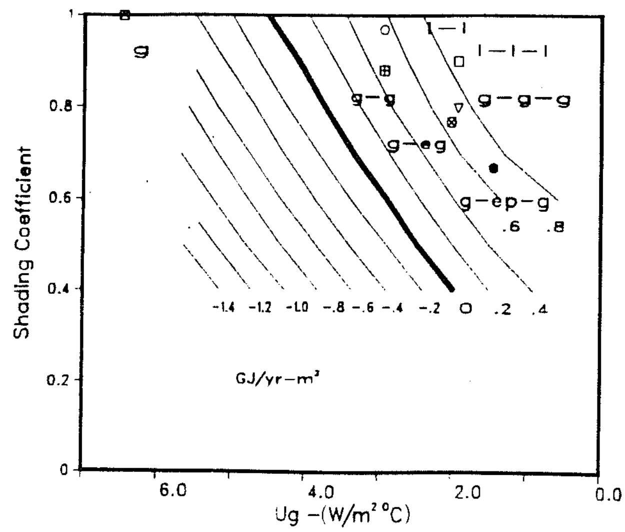


Fig. 3. Primary window size as a function of U-value, night insulation, and ratio of the cost of electricity (cooling) to the cost of gas (heating) for two shading coefficients for a south orientation in Madison, Wisc.



	U(W/m^{2}°C)	SC
g	6.46	1.0
g-g	2.87	0.88
g-g-g	1.8	0.8
g-eg	1.92	0.77
g-ep-g	1.32	0.67
1-1	2.87	0.97
1-1-1	1.80	0.9

g: 1/8" DS float glass
1: 1/8" low-iron sheet glass
e: low-emittance coating, e = 0.15
p: 4-mil polyester
All air gaps are 12.7 mm (1/2")
U-value: Standard ASHRAE winter conditions
SC: Standard ASHRAE summer conditions

Fig. 4. Net annual useful flux in Madison, Wisc., for a primary window area of 6.13 m^2 for an orientation due south. The performance of typical glazing properties is also shown.

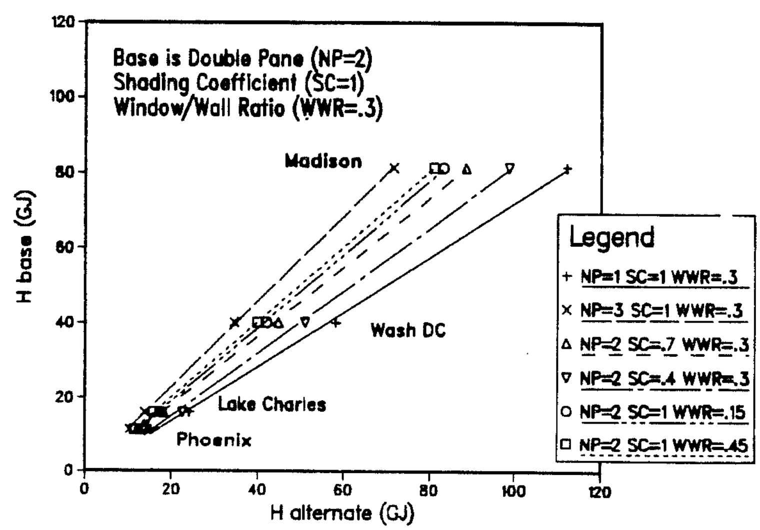


Fig. 5. Residential heating energy comparison for varying window properties and geographic locations for a south primary window orientation.