Fenestration Performance Analysis Using an Interactive Graphics-Based Methodology on a Microcomputer

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ABSTRACT

We show the development and implementation of a new methodology that can be used to evaluate the energy and comfort performance of fenestration in non-residential buildings. The methodology is based on the definition of a fenestration system "figure of merit." The "figure of merit" is determined by considering five non-dimensional performance indices representing heating energy, cooling energy, cooling energy peak, thermal comfort, and visual comfort. These indices were derived by performing a regression analysis of several thousand hour-by-hour building heat transfer simulations of a prototypical office building module using the DOE-2 simulation program.

The regression analysis resulted in a series of simplified algebraic expressions that related fenestration configuration variables to performance parameters. We implemented these equations in a "hypermedia" environment—one that integrates graphics, sound, animation, and calculation sequences—and created a prototype fenestration performance design tool. Inputs required by the program consist of geographic location, building type, perimeter space, and envelope definition. Outputs are the calculated performance indices for electricity and fuel use, peak electric load, and thermal and visual comfort.

INTRODUCTION

The advent of more powerful microcomputers during the past few years has resulted in correspondingly more powerful software packages that originally were designed for mainframe and minicomputer applications. Also, programs are specifically being written to take advantage of the microcomputer's ease and flexibility of use. In the building science field, a number of microcompter application programs have been created to calculate energy use performance. Hour-by-hour or bin-type calculation methods are usually employed and the user interfaces have generally been generic in nature and non-intuitive. Creating an alternative user environment is very time-consuming and costly and, until recently, was not justified because of the difficulty associated with the programming requirements of most microcomputers.

The Windows and Daylighting Group at a national laboratory has been involved in research related to analyzing and improving the energy and comfort performance of fenestration systems. In addition to developing new glazing materials, the authors have also spent some time defining new methods of analysis of fenestration systems so that critical design decisions can be made more efficiently, accurately, and timely. Several of our projects have resulted in a performance analysis methodology that begins with the creation of a large data base of hour-by-hour building energy simulations and ends with the derivation of simplified algebraic expressions that replicate the more detailed data base results. Our more recent studies emphasized the use of such simplified expressions as the foundation of our design tool work.

We describe in this paper the algorithmic development and implementation of a fenestration design tool that can be used to give a preliminary estimate of energy and comfort performance in non-residential buildings. Special emphasis is given to the user interface we developed, one that requires a minimum of keyboard inputs, is icon driven, graphically oriented, animated, accurate, and efficient.

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DATA BASE CONSTRUCTION

The foundation of the performance index concept is a large data base of DOE-2 (Simulation Research Group 1985) annual simulations of prototypical single-story commercial office modules (Figure 1) in Madison, WI, and Lake Charles, LA. The module has 4 perimeter zones consisting of 10 offices, each 4.57 m deep by 3.05 m wide, surrounding a central core zone of 929 m^2 floor area. Floor-to-ceiling height is 2.6 m with a plenum 1.07 m high. The exterior wall U-value was fixed at 0.28 $W/m^2{}^\circ C$.

Continuous strip windows were used in the exterior wall of each perimeter zone. Four glazing types and two shading devices were combined in several ways to simulate a representative sampling of realistic fenestration systems. Glazing area was parametrically varied at 0%, 15%, 30%, 45%, and 60% of the wall area. The glazing types were clear, bronze-tinted, reflective, and clear low-e. Results were obtained for single-, double-, and triple-pane units. Shading devices analyzed included a diffusing shade and a venetian blind.

We also simulated the daylighting performance of each perimeter zone using continuous dimming control for changing lighting levels. The illuminance setpoint was varied from 323 lux to 753 lux and the installed lighting power from 7.5 W/m^2 to 29 W/m^2. Daylighting levels were calculated at two reference points in each perimeter zone at a height above the floor of 0.76 m and depths of 1.5 m and 3.05 m.

HVAC system coil loads were isolated from the building thermal interactions by using a separate single-zone, constant-volume, variable-temperature system assigned to each zone. A constant furnace efficiency (0.6) and chiller coefficient of performance (COP) (3.0) converted these loads to energy usage values that formed the data base for electric and fuel usage. Future work will include options for varying efficiencies and COPs.

PERFORMANCE ANALYSIS METHODOLOGY

We developed five performance indices, each being a function of several fenestration system configuration variables. A regression analysis was performed on the DOE-2 parametric simulation data base, and simplified algebraic expressions were derived that accurately reproduced the simulated results. Multiple regression is an analytical technique for determining the best mathematical fit for a dependent variable as a function of many independent variables. The performance indices or dependent variables included three energy-related indices and two that dealt with thermal and visual comfort criteria. We envision the use of two types of indices: one directly related to the actual energy usage and the other a nondimensional index that varies between the values of 0 and 1 and represents the worst and best performers, respectively. Such a nondimensional scheme facilitates a more direct comparison of fenestration systems without regard to specific energy usage or comfort indicator amounts (Lawrence Berkeley Laboratory and Florida Solar Energy Center 1987).

Energy-related indices are representative of annual fuel use (heating), annual electricity use (cooling, lighting, fan), and peak electric demand. Other indices might be selected in future studies. The regression expression used to predict these quantities was:

$$\Delta E_i = \beta_{1i} \cdot U_g \cdot A_g + \beta_{2i} \cdot S_g \cdot A_g + \beta_{3i} \cdot k_d \cdot L \cdot A_f \qquad (1)$$

where ΔE is the incremental effect due to the fenestration system and subscript i refers to the particular energy-related index. The regression coefficients are denoted by β, and the equation has three components chosen to contain the energy effects from a particular building component: conduction ($U_g \cdot A_g$), solar radiation ($S_g \cdot A_g$), and lighting ($k_d \cdot L \cdot A_f$), where U_g is the overall conductance of the glazing, S_g is the solar heat gain coefficient, k_d is a daylighting correction term which is discussed below, and L is the lighting power density. A_g and A_f represent the window and floor area.

Nondimensional indices are obtained by using the following equation:

$$I_{\Delta Ei} = 1.0 - [\,(\Delta E_i - \Delta E_{imin}) / (\Delta E_{imax} - \Delta E_{imin})\,] \qquad (2)$$

where ΔE_{imax} and ΔE_{imin} are the minimum and maximum values of the incremental energy quantities, respectively.

The daylighting correction factor (k_d) is exponential and varies between 0 and 1. It is determined by a regression analysis and is a function of visible transmittance (ν), desired lighting level (C), and effective aperture (A_e), which is the product of window-to-wall ratio and visible transmittance. The following equation was used:

$$k_d = 1.0 - [\, \phi_{1i} + \phi_{2i} \cdot (C/v)\,] \cdot [\, 1. - e^{(\phi_{3i} + \phi_{4i} \cdot C)\, A_e}\,] \qquad (3)$$

where the ϕ's are the regression coefficients.

We derived a normalized thermal-comfort index using the following expression:

$$I_{TC} = 1.0 - \{\, [\,(1.0 - TC)/(1.0 - TC_{min})] \cdot [\, Ag/Ag_{max}\,]\,\} \qquad (4)$$

The quantity TC represents a parameter that was obtained by correlating the magnitude of direct solar radiation coming through a window to the percentage of people who would be dissatisfied with the rise in mean radiant temperature, calculated in accordance with methods developed by Fanger (1970). The amount of solar radiation was binned for the occupied hours during each DOE-2 simulation run. These values were then related to level of dissatisfaction. A proportional relationship was used to account for window area variations.

Weighted annual glare indices from the DOE-2 simulation runs were correlated with the effective aperture:

$$G = \delta_1 \cdot [\, 1.0 - e^{\delta_2 \cdot A_e}\,] \qquad (5)$$

where δ_1 and δ_2 are regression coefficients. The normalized glare index was:

$$I_G = 1.0 - [\,(G - G_{min}) / (G_{max} - G_{min})\,] \qquad (6)$$

We plan additional investigations of the comfort implications associated with fenestration. Initial results indicate that both of the comfort indices described above are not as sensitive to fenestration system variations as originally expected. This is partly due to the fact that we have defined annual performance indices based on many hours of occupancy, which tends to mitigate the discomfort extremes that can be experienced in some situations.

The final step in the task to evaluate the performance of fenestration systems and to establish a ranking procedure was to develop an overall figure of merit that combines all the index values into one number. The user can then directly compare the relative performance of the options being considered. The procedure gives the user the option of customizing the figures of merit for specific applications by assigning a weighting factor to each index. The figure of merit (F) would be derived from:

$$F = \Sigma\, w_i \cdot I_i \qquad (7)$$

where w_i represents the weighting factors assigned to the performance indices, I_i (fuel, electric, peak electric, and thermal and visual comfort). By making the sum of the weighting factors be equal to one, since indices are also expressed as values between 0 and 1, we also set the value of the figure of merit between 0 and 1. The system that best satisfies the design criteria is the system with the highest figure of merit. Other types of index value limits and types of weighting can be used; however, this very simplified, nondimensional technique illustrates the concept and was the one used in the design tool prototype discussed in the next section.

PERFORMANCE DESIGN TOOL DESCRIPTION

The results described above showed the feasibility of condensing DOE-2 results to relatively simple, compact expressions, i.e., indices that express performance relative to glazing properties. We used these equations to create a prototype fenestration performance design tool that uses a graphically oriented, very user-friendly interface. Our intent is for the prototype to be part of a much larger building envelope design tool (Selkowitz et al. 1986; and Schuman et al. 1988) that will interact directly with computer-aided design (CAD) systems and simplify the building design process. We selected a development environment called "hypermedia." Hypermedia is a term that implies the use of and access to computer graphics, video graphics (both still and motion), passive and active sound resources, and animation, all of which are utilized via sequential or non-sequential linking (hypertext).

The uniqueness of the program design stems from the use of icons to drive selections made by the user, enabling immediate branching and exploring to alternate parts of the program; a library of images and tabular data representative of different building types and window and shading systems to assist the user in making decisions and evaluating alternative configurations; and the use of animation in reporting calculated results and, although not yet implemented, to explain concepts such as daylighting and its effect on performance. This program represents one of the first uses of hypermedia-based software for analysis of building energy and comfort performance.

Several screens from the prototype are presented to give an indication of the user interface. We envision three main menu items: a performance run option, an optimization run option, and an option that permits access to a library of past runs. Figure 2 shows the first screen of the performance run option. Menu items are represented by icons that are displayed along the left-hand side of the screen. The first icon provides a selection of geographic locations. A map of the U.S. is presented on the screen with active locations highlighted. In our development effort they were Madison, WI, and Lake Charles, LA. Upon "clicking" the mouse button at either of these locations, the program jumps to the next screen, shown in Figure 3.

The second icon refers to selection of building type. We show as examples a commercial office building, a retail store, and an apartment building. Additional images would be used for libraries, warehouses, etc. The user selects the building by "clicking" the desired image and the program then presents the screen (shown in Figure 4) that is used to describe the perimeter zones of the building (icon 3).

The prototype has the capability to analyze four perimeter zones. They can be of any orientation. Data must be entered via the keyboard and the information requested would consist of orientation, floor area, lighting power density, desired illuminance, daylighting control strategy, and HVAC system type. Upon entering the information, the user "clicks" the word ENTER and the program goes to the next screen, which is used to describe the fenestration system parameters.

Data requested under the fourth icon (shown in Figure 5) consist of perimeter zone wall area, glazing area, glazing type, and shading system type. Users can analyze four fenestration systems for each zone simultaneously. We are implementing a library of glazing and shading systems so that the user can select from a wide range of glazing and shading options without knowing the detailed properties of each. This will help an inexperienced user to make informed decisions about a particular system. These libraries are accessible by clicking the words "Glazing Types" and "Shading Types."

Figure 6 shows output indices for several zones of the fenestration performance parameters discussed in the previous section. The bar charts are provided to give an indication of the relative performance of the four input fenestration systems. A composite results chart such as this enables users to make rapid decisions and either proceed or redefine the configuration variables. Figure 7 is an expanded view containing more detailed information for one of the "zone-parameter" boxes of Figure 6. It is obtained simply by clicking the appropriate box.

We have not yet implemented the last menu item, which refers to the application of the "weighting function" to calculate an overall fenestration system "figure of merit," nor have we completed the optimization run sequence. An optimization run is essentially the same as a performance run except that the last two menu items are reversed. In such a case, the user specifies a desired "weighting function" and a solution is then generated that gives the fenestration system that best meets the weighting function objectives. We are currently implementing this procedure into the model.

CONCLUSIONS

We have discussed the computational methodology and implementation of a fenestration performance design tool that building designers could use to determine the energy and comfort impact of fenestration. Our intent has been to simplify the design decision process yet maintain a sufficient level of mathematical sophistication so that potential users have confidence in the calculated results. We believe we have achieved these objectives by using regression analysis in conjunction with detailed hour-by-hour building heat transfer simulations to define the solution algorithms and by creating a unique graphics-based user interface with hypermedia software. The ability to find fenestration solutions that provide trade-offs between cost, energy, and comfort performance is a significant feature of this tool.

We began exploring the use of "hypermedia" (the integration of computer graphics, still and motion video, sound, animation, etc., with those tasks normally associated with computers) as a means to create a dynamic user environment that enhances the overall building design process. We intend to complete development of the design tool discussed in this paper in the immediate future. Our current focus is on the implementation of the optimization algorithms and an increase in the size of the data base so that other fenestration systems and other geographic locations and building types can be analyzed. Upon completion, users will be asked to evaluate the performance of the tool and suggest improvements for the next prototype version. Eventually this tool is intended to be part of a more comprehensive "advanced design tool" incorporating the hypermedia techniques discussed herein with an "advisor" function provided by expert system software, and linked to imaging and CAD software to provide two- and three-D representations of proposed designs.

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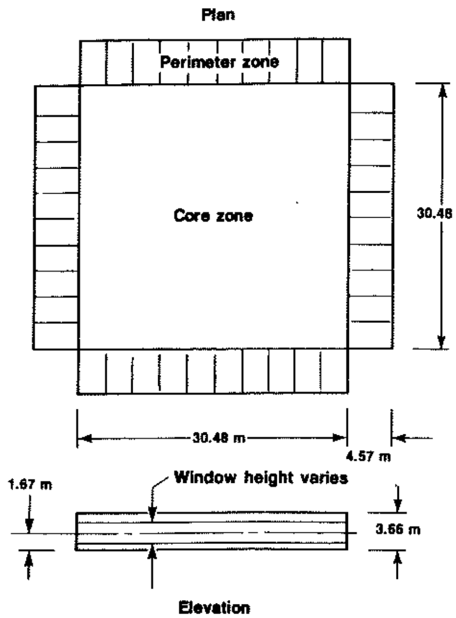

Figure 1. Plan of simulated office building showing alternative window-to-wall ratios. Module consists of a 929 m^2 core surrounded by 4.57m deep perimeter zones, each divided into 10 modules 3.05 m wide.

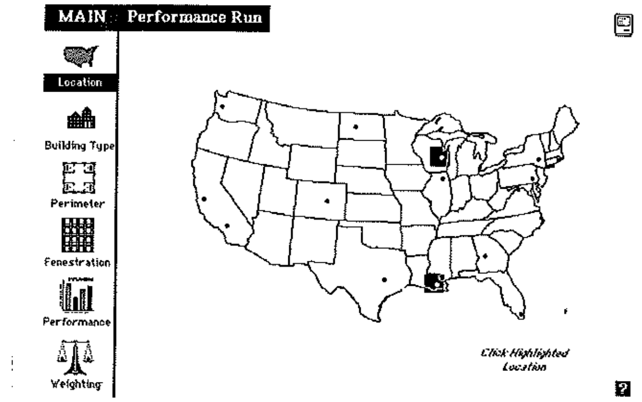

Figure 2. First screen of the fenestration performance run corresponding to the first menu item in the menu displayed along the left side of the screen. A selection of geographic locations is made by clicking the desired highlighted location.

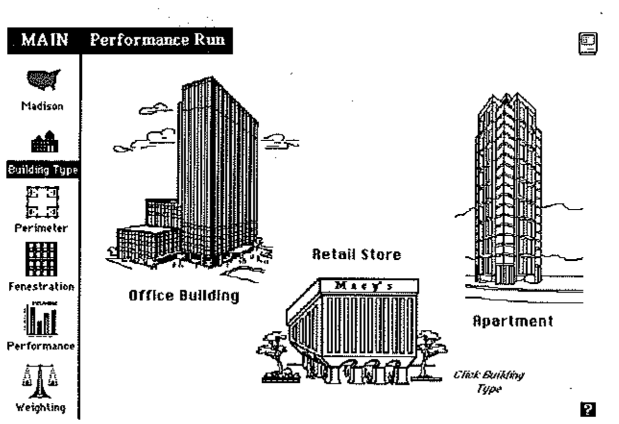

Figure 3. Second screen of the fenestration performance run. A selection of building type is made by clicking the appropriate building type.

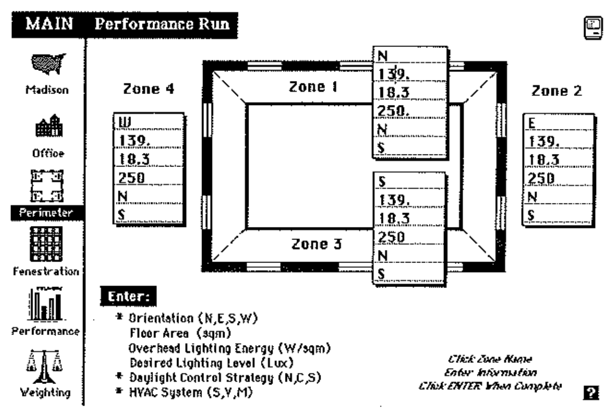

Figure 4. Third screen of the fenestration performance run. Data inputs that define the characteristics of the perimeter zones are entered via the keyboard.

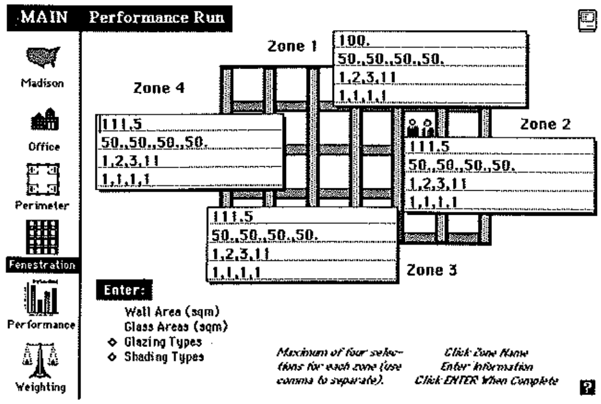

Figure 5. Fourth screen of the fenestration performance run. Data related to the characteristics of the fenestration system are entered via the keyboard.

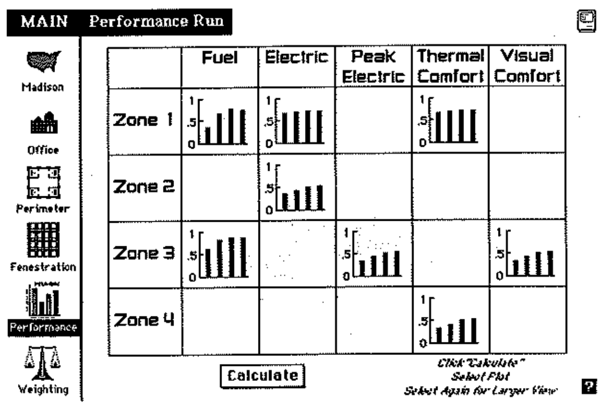

Figure 6. Fifth screen of the fenestration run. This screen represents a consolidated output that graphically shows the performance indices for each zone for each input fenestration system.

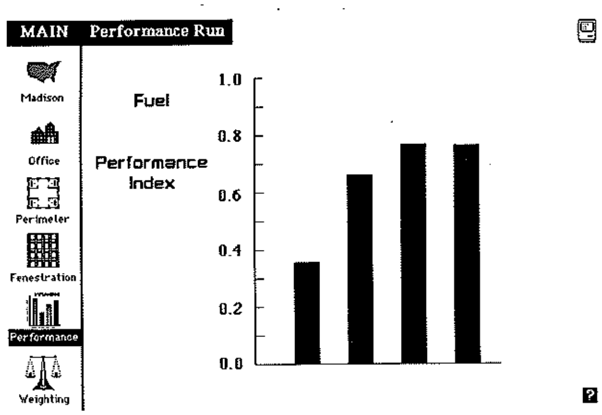

Figure 7. Sixth screen of the fenestration performance run. An expanded view of the fuel performance index is shown for a particular zone for the four input fenestration systems.