# DEVELOPMENT OF A METHODOLOGY TO EVALUATE THE ENERGY AND COMFORT PERFORMANCE OF FENESTRATION

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## ABSTRACT

This paper describes the development of a new concept for analyzing the performance of fenestration systems. We show the derivation of five indicators that can be combined in a variety of ways so that both qualitative and quantitative judgements can be made regarding total fenestration performance. The five indices consist of three related to energy: fuel (heating), electric (cooling), and peak electric demand; and two to comfort: thermal and visual. Performance comparisons of different systems are made possible by introduction of a non-dimensional user-defined weighting function that specifies the relationship between the five indices. A "figure of merit" is then calculated by combining the index values and weighting factors to provide a direct comparison between fenestration systems.

The indices were derived by performing a multiple regression of several thousand hour-by-hour building heat transfer simulations of a prototypical office building module using the DOE-2 simulation program. From this regression analysis, we derived a series of simplified algebraic expressions that related fenestration performance to configuration variables. We then incorporated this methodology as the computational engine within a prototype fenestration design tool on a microcomputer using "hypermedia" concepts for the user interface. A "hypermedia" environment is one that integrates computer graphics, video, sound, animation, etc. with calculation sequences. This first prototype represents a significant developmental step toward our longterm goal of an overall building envelope design tool.

## INTRODUCTION

Energy consumption, thermal comfort, visual comfort, aesthetics, and view access are a few of the concerns that building designers must contend with during preliminary design stages. These items are specifically relevant to the building envelope and each can be addressed using many different design philosophies or rules-of thumb based on previous experience. Although the advent of computers, particularly the availability and use of computer aided design (CAD) hardware and software, has had a significant impact on analytical and drafting tasks, there currently does not exist a capability that integrates the design task requirements for a whole building with appropriate energy concerns.

The Windows and Daylighting Group at Lawrence Berkeley Laboratory, as part of our research into improving the energy and comfort performance of fenestration, has been involved in developing new methods to incorporate energy related concerns within the building design process. Our work has involved concept definition (Selkowitz, et.al. 1986), methodology derivation (Sullivan, et.al. 1987), and prototypical design tool development (Schuman, et.al. 1988). Our efforts have progressed simultaneously with the development and commercial availability of more sophisticated computer software and hardware that facilitates our vision of an advanced building design tool.

We describe in this paper the algorithmic development and implementation of one segment 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 that we developed, one which requires a minimum of keyboard inputs, is icon driven, graphically oriented, animated, accurate, and efficient.

## 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 a prototypical single-story commercial office module (Figure 1) in two climatic extremes: Madison, Wisconsin and Lake Charles, Louisiana. The module has four perimeter zones consisting of ten offices, each 4.57m deep by 3.05m wide, surrounding a central core zone of 929m$^2$ floor area. Floor-to-ceiling height is 2.6m with a plenum of 1.07m height. The exterior opaque wall U-value was fixed at 0.28 W/m$^2$ 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 perimenter zone at a height above the floor of 0.76m and at depths of 1.5m and 3.05m.

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 (3.0) converted these loads to energy usage values that formed the data base for electric and fuel usage. Our future work will include options for varying efficiencies and COP's.

## 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 or other quantitative measures 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 non-dimensional 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).

In our current tool prototype, 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 has the form:

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

where $\Delta E$ 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 $\beta$, 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.

Non-dimensional indices are obtained by using the following equation:

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

where $\Delta E_{imin}$ and $\Delta E_{imax}$ are the minimum and maximum values of the incremental energy quantities.

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 (v), 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:

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

where the $\phi$'s are the regression coefficients.

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

$$I_{TC} = 1.0 - \{ [(1.0 - TC)/(1.0 - TC_{min})] \cdot [A_g/A_{g max}] \} \qquad (4)$$

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 that 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 $\delta_1$ and $\delta_2$ 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 hourly, daily, and seasonal 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, 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 weighted overall 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.

## ENVELOPE PERFORMANCE DESIGN TOOL DESCRIPTION

Selkowitz, et al. (1986) defined a concept for an advanced computer-based building envelope design tool. An interactive workstation was described in which both the qualitative and quantitative aspects of the building design process were accommodated within the same design tool which utilized images (buildings, landscapes, models, documents, etc.), expert systems (knowledge bases, i.e. lighting design, site planning, HVAC design, etc.), and data bases (design criteria, utility rates, climatic data, etc.) in addition to more traditional simulation models. The integration of these tool elements is schown schematically on Figure 2 and can be described as a "hypermedia" environment. "Hypermedia" implies the usage of and access to computer graphics, video graphics (still and motion), passive and active sound resources, animation, and data bases, all of which are utilized via sequential or non-sequential linking (hypertext) that is controlled by the user. These elements of the user interface are meant to support more efficient user access to the knowledge base contained within the tool.

We are using these concepts in the development of several prototype design and analysis tools. Schuman, et al. (1988) describes an ambitious effort involving creation of a prototype daylight design tool. Figure 3 shows the workstation consisting of a Macintosh computer, video monitor, and optical disk player. The designer uses the microcomputer screen to control access to thousands of images that reside on the optical disk using a program called HyperCard. A single HyperCard screen contains text, data, graphics, and/or images as well as the linkage information that contains the user-selected access to other screens. The software "scripts" that activate these linkages are provided by HyperCard through its computer language called HyperTalk. Prior to the availability of HyperCard, developers had to be familiar with lower level programming languages and also the special software requirements associated with the Macintosh for screen design and control.

The structure of this hypermedia software enables users to define their own paths and/or areas of interests. Within the overall daylighting design tool, one of the paths that will be available involves calculating fenestration performance using the algorithmic methodology discussed in the previous section. There, we showed the feasibility of condensing DOE-2 results to relatively simple, compact expressions, i.e., indices that express total performance relative to glazing properties. Simulation results must be provided quickly in an interactive tool, so this computational approach using indices is well suited for this purpose. We used these indices equations to create a fenestration performance design tool that uses a graphically-oriented, very user-friendly interface. The uniqueness of the program design stems from: the use of icons to drive selections made by the user enabling immediate branching and exploration to alternate parts of the program; (2) 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 (3) 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 this first prototype user interface. We envision three main menu items: a new performance run option, an optimization run option, and an option that permits access to a library of past analyses. Figure 4 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 location. A map of the U.S. is presented on the screen with active locations highlighted. In our development effort they were Madison, Wisconsin and Lake Charles, Louisiana. Upon "clicking" the mouse button at either of these locations, the program jumps to the next screen shown on Figure 5.

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 which then sends one to a screen to define perimeter zone parameters. The prototype tool has the capability of analyzing four perimeter zones. Zone data is entered via the third icon using the keyboard. The information requested includes orientation, floor area, lighting power density, desired illuminance, daylighting control strategy, and HVAC system type. Additional help screens and menus assist selection of these values. Once the perimeter zone parameters have been selected, the fenestration details are defined by selecting the fourth icon. Data requested under the fourth icon (Fenestration), 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 hypermedia libraries will eventually include a full range of animation and video techniques to describe each entry as well as having more traditional numerical values.

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. We also provide 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 similar to a performance run except that the last two menu items are reversed. In such a case, the user specifies a desired "weighting function" and the tool determines 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 prototype 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 tradeoffs between cost, energy, and comfort performance is a significant feature of this tool.

To enhance the effectiveness of the tool, we use "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 2- and 3-D representations of proposed designs.

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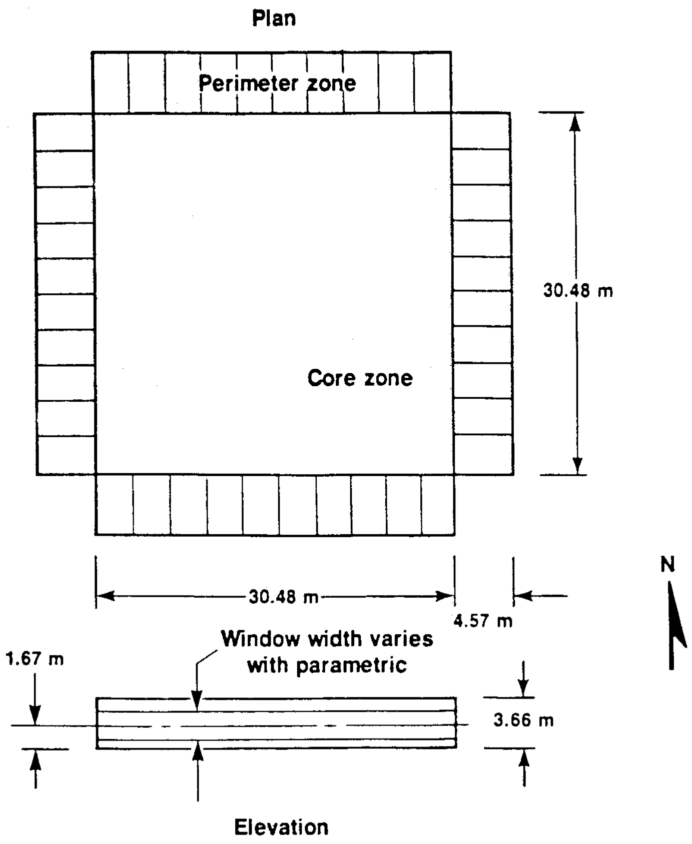


Figure 1. Plan of simulated office building showing alternative window-to-wall ratios. Module consists of a 929m$^2$ core surrounded by 4.57m deep perimeter zones, each divided into 10 modules 3.05m wide.

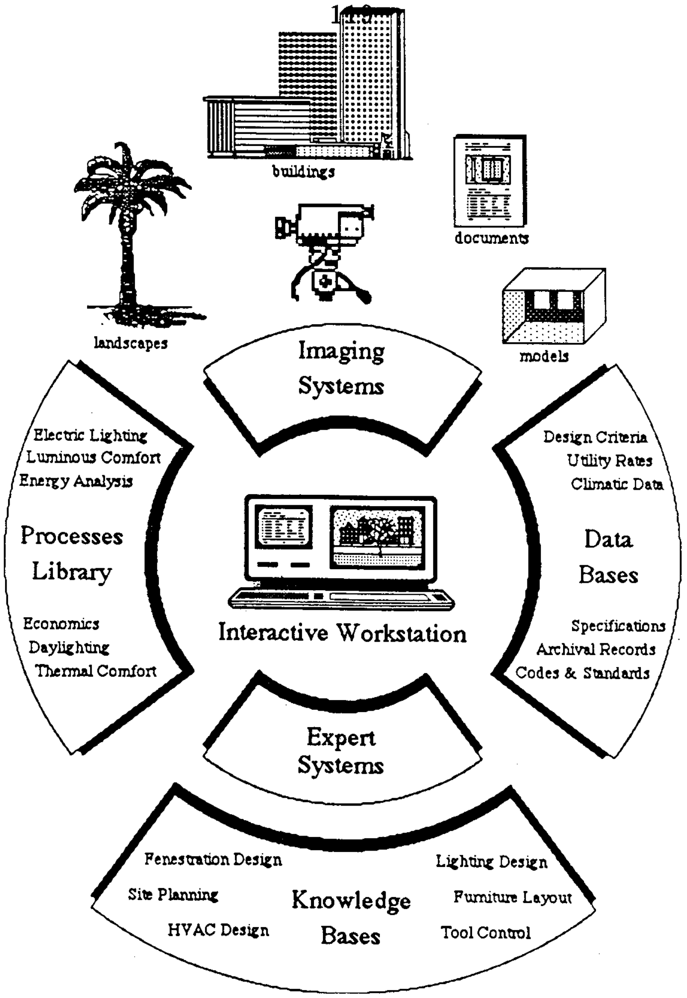


Figure 2. Schematic of the concept of an advanced computer-based building envelope design tool, showing the major tool elements and examples of their tentative contents.

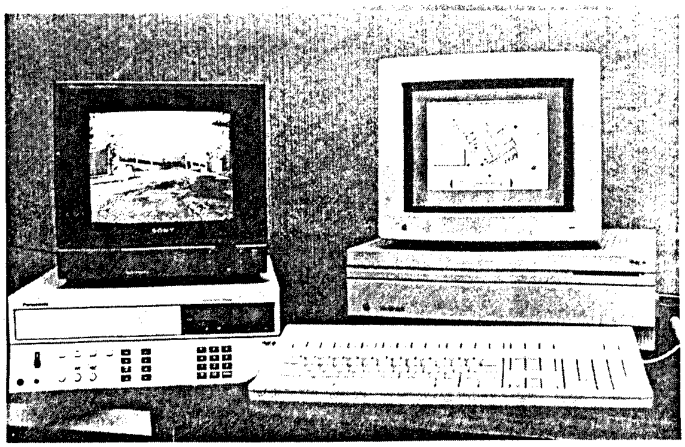


Figure 3. Prototype daylighting design tool workstation consist of a microcomputer, optical disk player, and color video monitor.

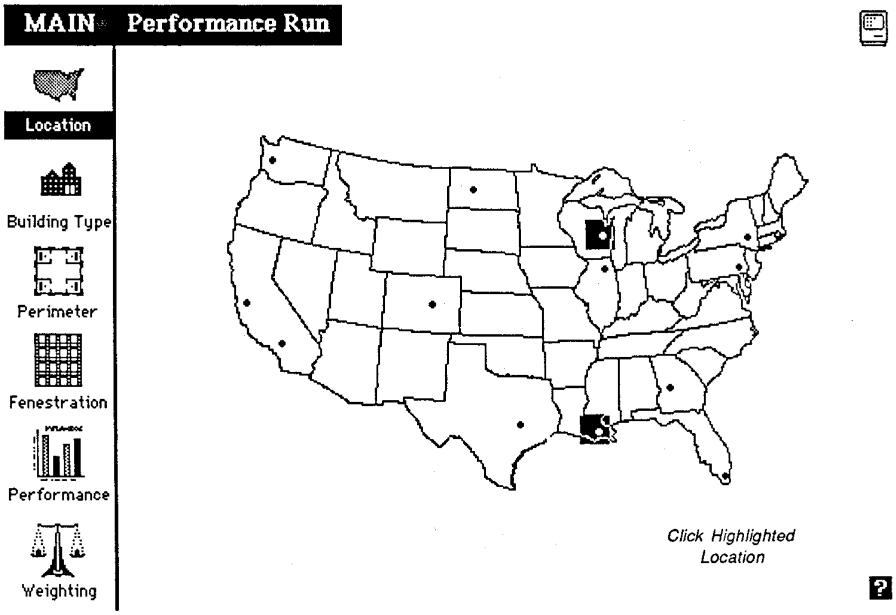


Figure 4. Prototype fenestration performance design tool screen for selection of geographic location. A selection is made by clicking the desired highlighted location.

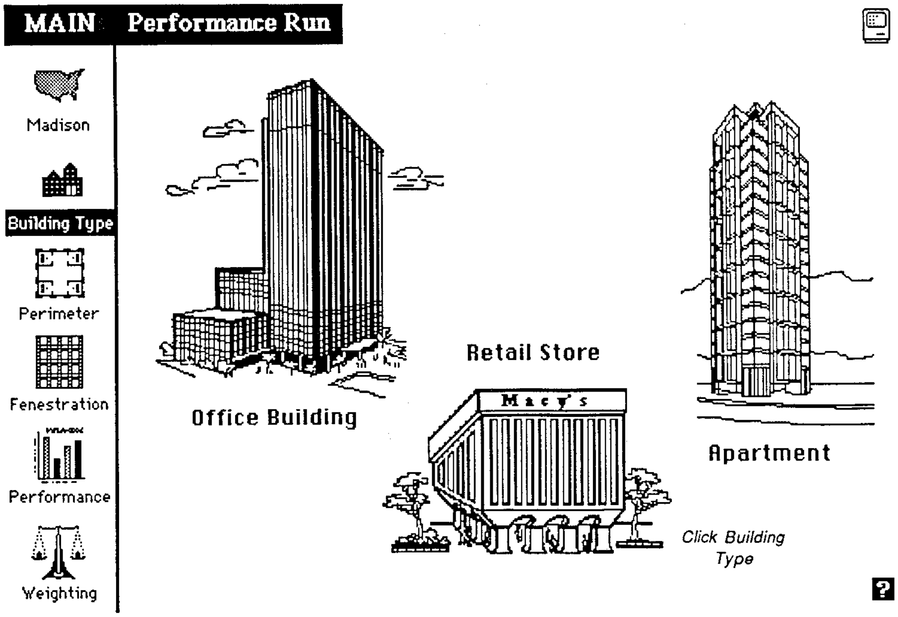
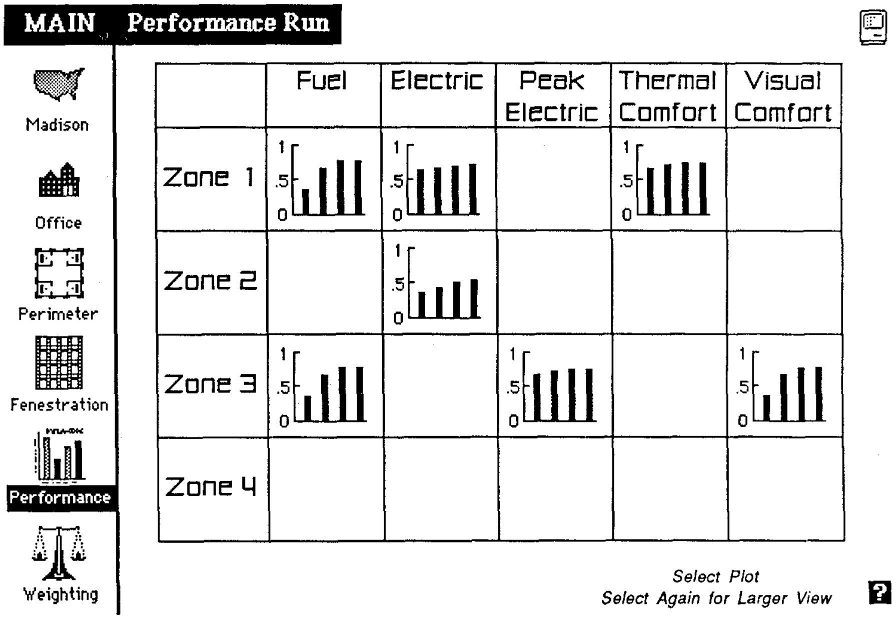


Figure 5. Prototype fenestration performance design tool screen for selection of building type. A selection is made by clicking the appropriate building type.



| | Fuel | Electric | Peak Electric | Thermal Comfort | Visual Comfort |
|---|---|---|---|---|---|
| Zone 1 | 1<br>.5<br>0 | 1<br>.5<br>0 | | 1<br>.5<br>0 | |
| Zone 2 | | 1<br>.5<br>0 | | | |
| Zone 3 | 1<br>.5<br>0 | | 1<br>.5<br>0 | | 1<br>.5<br>0 |
| Zone 4 | | | | | |

*Select Plot*
*Select Again for Larger View*

Figure 6. Prototype fenestration performance design tool screen for presentation of composite results. Results are shownfor five performance parameters, four perimeter zones, and four fenestration systems.