Improving Information Technology to Maximize Fenestration Energy Efficiency

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ABSTRACT

Software is making an impact on the design and deployment of efficient fenestration products by making performance ratings widely available. Such ratings have influenced codes and aided voluntary market transformation programs.

Software tools developed to date have focused on determining product properties, such as the solar heat gain coefficient (SHGC), U-factor, and visible transmittance. However, to fully realize the potential for energy savings from fenestration products, software needs to be improved in the following three key areas:

1. *modeling of fenestration product details since, for highly efficient products with low heat flow, these details become the significant areas for improving performance;*
2. *quantifying the relationship between energy efficiency and the more important non-energy benefits, such as thermal and visual comfort and condensation; and*
3. *linking applications level tools (which consider the building and location where the fenestration product will be installed) to fenestration product modeling tools for users to understand how specific products perform in specific buildings under particular installation conditions.*

This paper addresses how future window modeling software can—and needs to—address these three topical areas in order to help promote the development of efficient window products and their effective use.

INTRODUCTION AND BACKGROUND

Annual heating and cooling energy loads through fenestration products in both residential and commercial buildings are a significant fraction of national energy requirements. In the residential sector, 1.34 and 0.37 quads are required for heating and cooling, respectively (DOE 2000). In commercial buildings, cooling energy use to compensate for fenestration product solar heat gain is estimated at 0.39 quads; heating energy use to compensate for heat loss through fenestration products is estimated at 0.19 quads. Advanced products offer the potential to reduce these energy uses by at least 50% (Frost et. al. 1993). Potential electric lighting savings from fenestration products are estimated at 0.4 quads if daylight can be used effectively so that electric lighting in commercial building perimeter zones can be reduced.

Software has begun to make an impact on the design and deployment of efficient fenestration products by making fenestration product performance ratings widely available. These ratings, which are determined in part using software programs such as WINDOW/THERM/Optics, VISION/FRAME, and WIS, can now easily be used by architects, engineers, professional fenestration product specifiers, and consumers. Information on the properties of fenestration products has also influenced state and national codes (IECC, ASHRAE 90.1) and aided voluntary market transformation programs, such as the Efficient Windows Collaborative and the Energy Star Windows program, which promote efficient fenestration products.

Most software development to date has focused on modeling fenestration product properties such as the solar heat gain coefficient (SHGC), U-factor, and visible transmittance. For example, software developed by the authors is shown in Figure 1. Optics (Optics5 2001) develops spectral transmittance and reflectance data for laminates and applied films,

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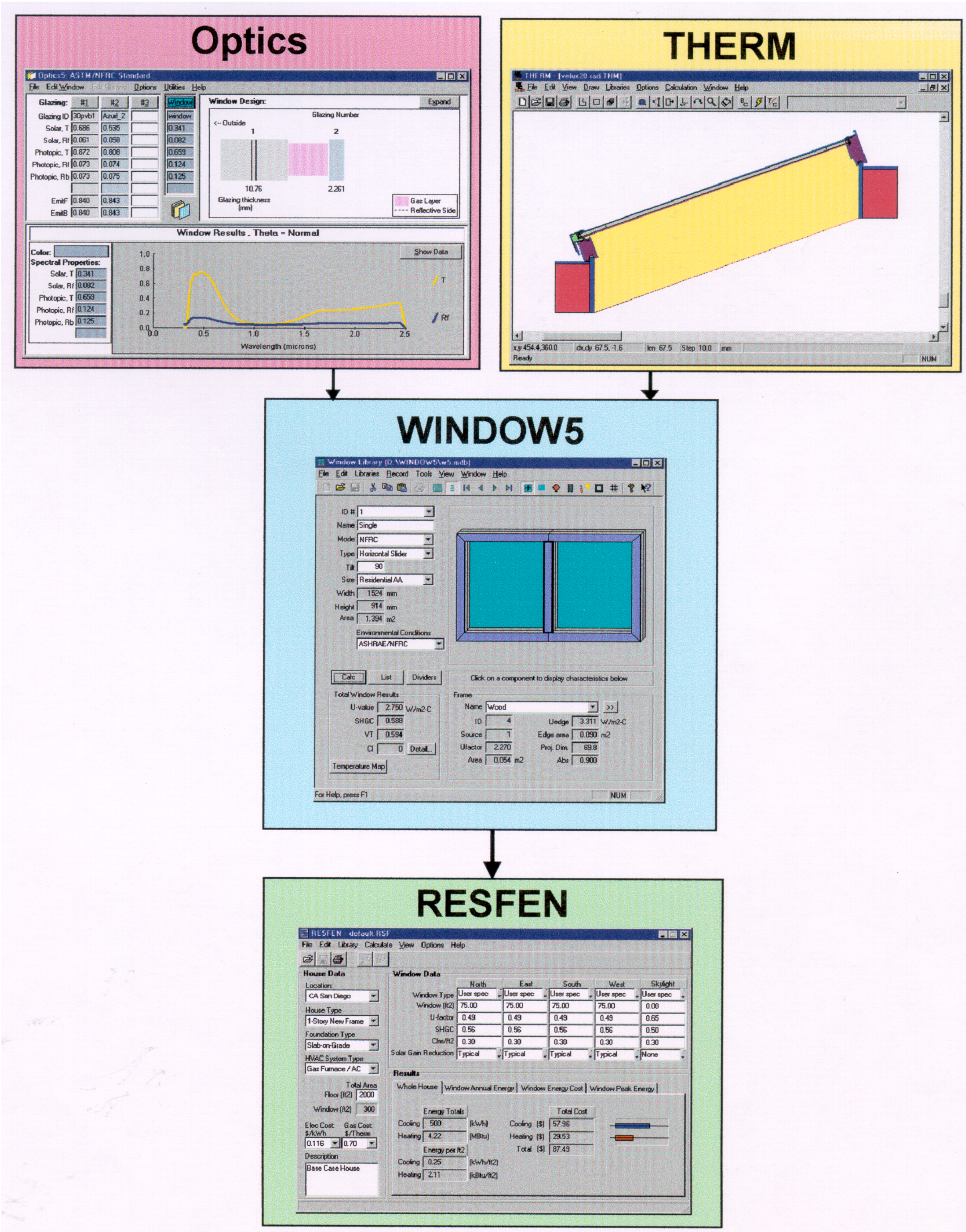

Figure 1 *Currently available software programs for analyzing fenestration product energy impacts.*

based on the properties of the components. THERM (Finlayson et al. 1998) models two-dimensional heat transfer through fenestration product frames. WINDOW (LBL 1994; Arasteh et al. 1998; Arasteh et al. 2000) incorporates the results of these two programs and computes total fenestration product properties: (1) the SHGC, which quantifies the fraction of solar gain incident on the fenestration product, which turns into heat gain inside an interior space; (2) the U-factor, which quantifies the heat lost when there is a temperature differential on the two sides of a fenestration product unit; and (3) the visible transmittance, which quantifies the fraction of visible light transmitted through the fenestration product. Programs that quantify the impacts of fenestration product properties on whole buildings, such as RESFEN (Mitchell et al. 1999) for residential buildings, have also been developed.

To help fully realize the potential for energy savings from fenestration products, software needs to be improved in the following three key areas:

4. *Modeling of fenestration product details.* Precise details of fenestration product construction and performance, such as solar heat gain from the fenestration product frame and divider, three-dimensional convective effects, and glazing deflection, need to be modeled more accurately than is currently the norm because in highly efficient products with low heat flow, these details become the significant areas for improving performance. This area of future software development is discussed below.
5. *Quantifying the relationship between energy efficiency and non-energy benefits* such as thermal and visual comfort, condensation and fading from ultraviolet (UV) portions of the spectrum. These are the parameters that occupants (and thus designers, contractors, and fenestration product manufacturers) care about most. Typically, improving fenestration product performance in these areas improves a product's energy efficiency as well. The issue of improving software capabilities to model "comfort" parameters is examined later.
6. *Linking applications level tools (which consider the building and location the fenestration product will be installed in) to fenestration product modeling tools* so that users can evaluate how improvements in a fenestration product will affect its performance in a building under particular installation conditions. In the future, issues related to specific applications of fenestration products will likely play a larger role in energy savings than will developing a "one size fits all" efficient fenestration product. Developments in modeling fenestration product applications are addressed below.

IMPROVING SOFTWARE TO MORE ACCURATELY MODEL DETAILED FENESTRATION PRODUCT FEATURES

Existing software tools for quantifying fenestration product heat transfer include WINDOW, THERM, WIS, and VISION/FRAME. The accuracy of these tools has increased during the past decade, but, although these programs routinely show "good agreement" (Arasteh et al. 1994) with test results, improvements are necessary if these codes are to properly credit the features that represent the next frontier in fenestration product energy efficiency. Important areas for improvement are

- *Frame cavity heat transfer (convection and radiation modeling)* because the insulating value of future high-performance frames will be derived mainly from frame cavities. Currently, correlations from several sources are used for both convective and radiative effects. While a detailed radiation model (element to element view factors in a two-dimensional heat transfer model) can be used to accurately calculate radiative effects in frame cavities, correlations currently in use for determining convective heat transfer provide varying results. CFD simulations have been shown to provide excellent agreement with experimental data (Gustavsen et al. 2001), but such simulations are not practical for everyday use and improved correlations or simplified CFD models are needed for routine calculations. Roth (1998) has shown how gap convective heat transfer coefficients can vary by a factor of three, depending on the correlation used. Figure 2 shows how the frame U-factor for a typical vinyl window frame varies by approximately ±10%, depending on which correlations are used (ASHRAE or CEN) and how they are interpreted.
- *Improving off-normal solar heat gain effects.* Currently, total product SHGCs are reported at normal incidence while glazing solar optical properties are calculated at normal and off-normal angles of incidence. Solar heat gain resulting from the fenestration product frame and divider is simplified for normal incidence calculations and not reported for off-normal angles of incidence. As glazing system solar heat gain is reduced in future highly efficient fenestration products, the solar gains of frames and dividers (including effects from self-shading) will become more significant. Figure 3 shows an example of how using fenestration product specific geometry will improve the accuracy of total fenestration product SHGC calculations.
- *Three-dimensional conductive, convective, and radiative corner effects, as well as three-dimensional noncontinuous thermal bridges*, which are currently ignored in fenestration product modeling software. Such effects will have a proportionally greater impact as product total heat transfer decreases, particularly on surface temperatures and thus impacting condensation.
- *Glazing deflection*, which is currently ignored in simulation software; as fenestration products become more insulating, the impacts of temperature- and pressure-induced deflection may increase if not properly accounted for in product design. Bernier and Bourret (1997) show how center-of-glass U-factors can rise 4% to 6% for typical insulating glass products offered today, with the higher percentage increases coming from higher performing products.
- *Variable film coefficients*, which are currently not part of modeling procedures; inclusion of these coefficients will increase the accuracy of heat-transfer and surface temperature predictions (Curcija et. al. 1998; Zhao et. al. 1996).

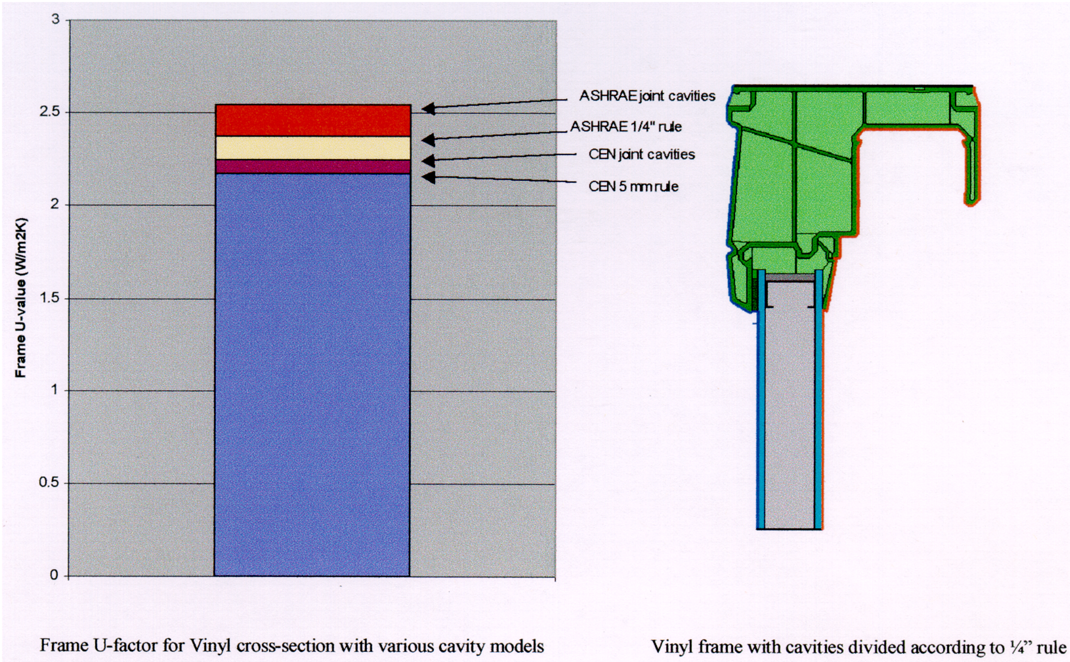

Figure 2 *Frame U-factors for a typical vinyl frame can vary by approximately ±10%, depending on the cavity model chosen and how it is interpreted.*

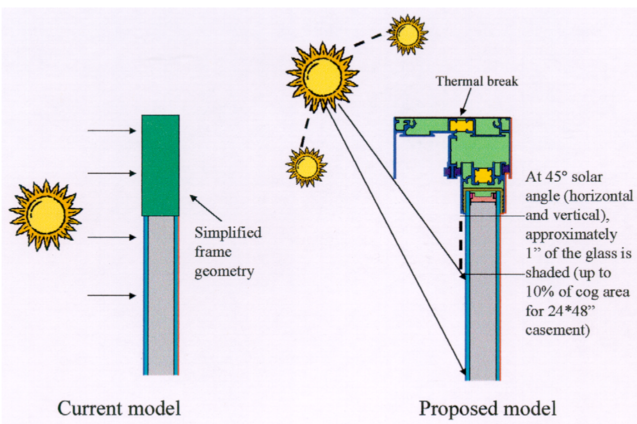

Figure 3 *Improvements to the current methodology to analyze window frame heat transfer will improve the computation of the frame heat transfer through the glazing as well as the impacts of frame self-shading and frame-glass shading.*

- *Optically complex (i.e., nonspecular) products* are not currently considered in simulation software. These are likely to be important in the next generation of energy-efficient fenestration products, particularly commercial glazing systems that emphasize daylighting. With such products, the angular properties of the fenestration product no longer vary in a predictable manner. Performance data must be determined as a function of incoming solar radiation over a whole hemisphere. Figure 4 is an example of how SHGCs can vary tremendously based on solar position for such products (Klems et al. 1996); it shows bi-directional SHGCs for double glazing with a venetian blind.

IMPROVING SOFTWARE TO MORE ACCURATELY MODEL FENESTRATION PRODUCT NON-ENERGY BENEFITS

Although the focus of fenestration product simulation software programs to date has been on energy properties, several energy-related effects that are the primary drivers in fenestration product selection have not been addressed directly. These include thermal and visual comfort, condensation, and UV fading. The fundamental physical phenomena underlying these effects are the same as those involved in fenestration product energy efficiency; thus, these effects can be addressed at the same time and in the same manner as energy efficiency. Focusing on these effects will serve fenestration product specifiers and help integrate fenestration product energy efficiency with other fundamental issues that are important to building occupants.

Fenestration product thermal comfort is a direct consequence of fenestration product surface temperatures and solar transmittance. Surface temperature plots for a fenestration product under a set of specific conditions can be generated by fenestration product energy analysis software (see Figure 5). Such surface temperatures, along with transmitted solar radiation information and interior thermal conditions, can be used (see Figure 6) to characterize human thermal comfort/discomfort. An understanding of human thermal comfort can lead to design and installation of heating, ventilation, and air-conditioning (HVAC) systems that will better meet the needs of building occupants while minimizing energy use. Use of super-efficient fenestration products can reduce the need for HVAC capacity and distribution systems. When we link fenestration product simulation and comfort software, opportunities for minimizing HVAC system size and energy use will be better understood.

Condensation on fenestration products is the number one source of fenestration product complaints and is a cause of rot and mold. Condensation is a function of interior humidity levels and fenestration product surface temperatures. Interior humidity levels are determined by occupancy, but fenestration product surface temperatures are directly related to fenestration product heat transfer. Temperature images of a fenestration product's surface, such as those in Figure 5, can be used to help understand and minimize condensation.

Spectral properties of fenestration systems, critical for understanding solar heat gain, are also the building blocks for understanding occupants' visual comfort and the fading of interior surfaces. Visual comfort and fading are significant factors in fenestration product selection; their relative importance depends on building type. Spectral data can be translated into predictors of fading or input to ray-tracing software, which can provide qualitative and quantitative descriptions of visual comfort (see Figure 7).

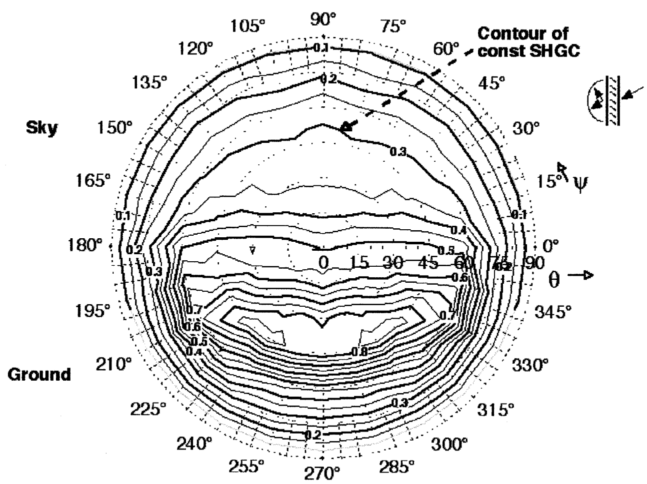

Figure 4 *The solar heat gain coefficient of a clear double glazing with a between-pane venetian blind, plotted as a contour on a polar representation of the two angles determining the incident direction. The blind slats are tilted downward at 45°, as illustrated by the inset figure. The incident angle, θ, is represented as the radius in the plot, while the angle ψ is the azimuthal angle of the sun direction projected onto the plane of the glazing. In effect, a point on the plot gives the sun direction as seen through the glazing. The horizontal axis (0° and 180°) corresponds to the horizon; directions lying below the axis (ψ > 180°) would correspond to radiation reflected from the ground. The center of the plot is normal incidence.*

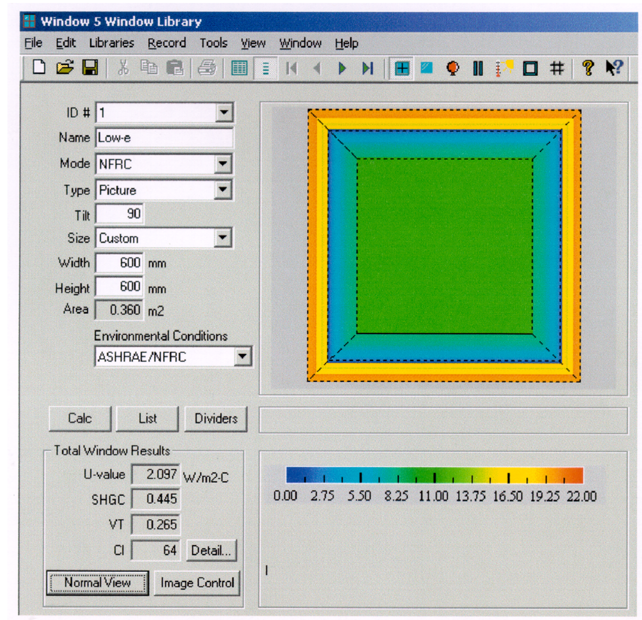

Figure 5 *Sample screen showing WINDOW5's temperature map of a typical fenestration*

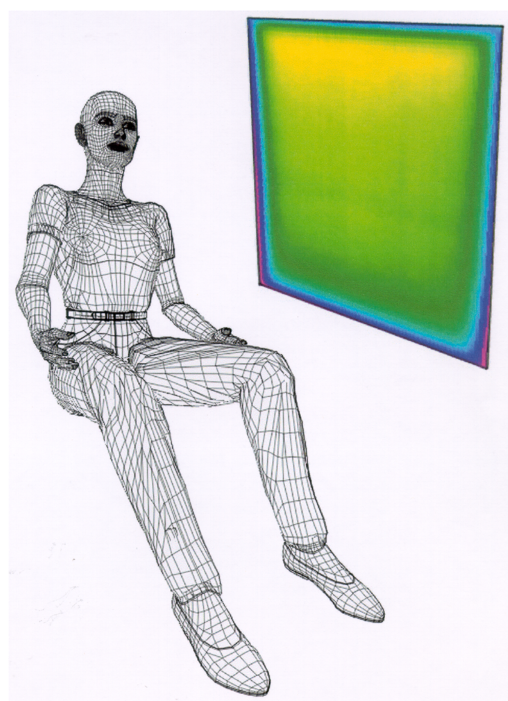

Figure 6 *Software that models human physiology and thermal comfort can be integrated with fenestration product surface temperatures to analyze thermal comfort implications from fenestration products.*

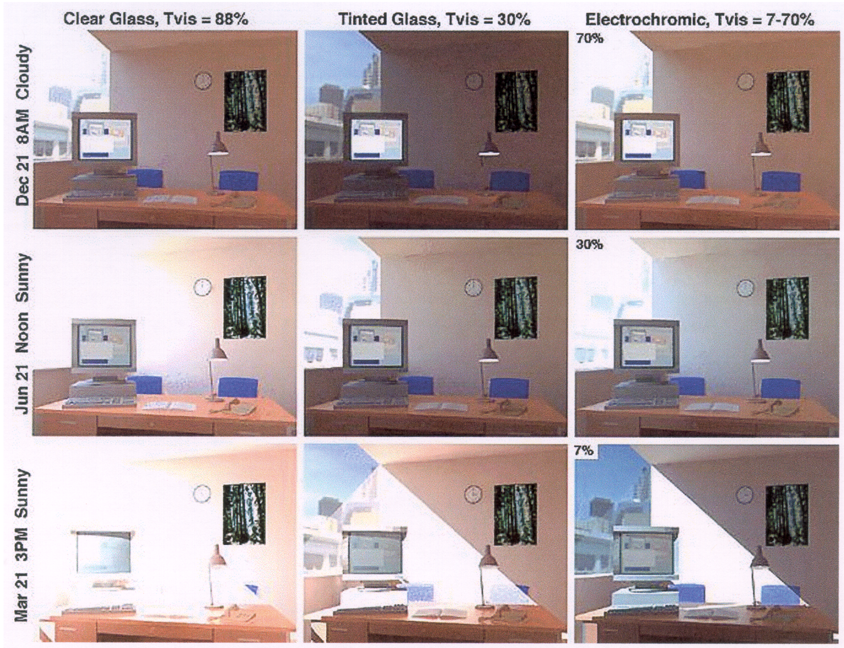

Figure 7 *Images from RADIANCE showing how ray-tracing software can be used to provide images of daylighting quality and quantity.*

As software is improved to model the effects discussed in this section, specifiers and consumers will be able to select fenestration products with improved thermal and visual comfort. Since these properties typically correlate strongly with energy efficiency, these features will promote increased use of efficient products.

EXPANDING SOFTWARE TOOLS TO MODEL SPECIFIC FENESTRATION PRODUCT APPLICATIONS

In addition to improving the modeling of energy and energy-related fenestration product properties, optimizing fenestration product energy efficiency in the field will require that simulation software include improvements in applications-based tools because total fenestration product energy use depends on specifics of the fenestration product's application, such as climate, building type, orientation, and use. Trade-offs among properties can be significant; these can be addressed at an applications level.

Applications analysis is important to fenestration product selection because, unlike appliances or lights or insulation, which perform "as expected" with few applications-specific variances, fenestration products perform very differently in different applications. This is particularly true as the fenestration products become more efficient. In the residential sector, for example, trade-offs between useful solar gains and conductive losses become critical and are impacted by the primary orientation of the glazing. A west-oriented house may be adversely affected by solar gains and cooling loads and the optimum window may be one with a low SHGC, while in the same climate, a similar house with primarily south-facing glazing may be able to effectively utilize winter solar gains to offset heating needs and, in this case, the optimum glazing may be a high SHGC product. In commercial buildings, the trade-off between daylight and electric lighting is constantly changing. For manufacturers, the cost of developing a single product that will perform well in all applications should be considered in light of the potential lesser cost resulting from providing a range of options so consumers can choose an optimum product for a particular application. Thus, applications-based tools will help manufacturers and consumers optimize fenestration product energy savings.

Several tools that are currently available give a glimpse of the full potential of information technology for achieving optimal energy savings from fenestration products. These tools are described below, followed by a discussion of how they may be combined into an effective applications-based tool.

- WINDOW analyzes fenestration product heat transfer under a set of specific environmental conditions and summarizes results in the form of common indices (U-factor, SHGC, visible transmittance, condensation index, etc.).
- RESFEN (Mitchell et. al. 1999) allows users to estimate the annual cooling and heating energy impacts of fenestration products (given their properties, calculated by WINDOW5) in a given building type in any climate in the U.S. Behind RESFEN's simple one-page input screen (see Figure 8) is the DOE2.1E hourly energy simulation program (REFERENCE). Although RESFEN is currently limited to residential prototypes, a similar tool (COMFEN) could model commercial building prototypes.
- The NFRC Certified Products Directory (CPD) is a list-

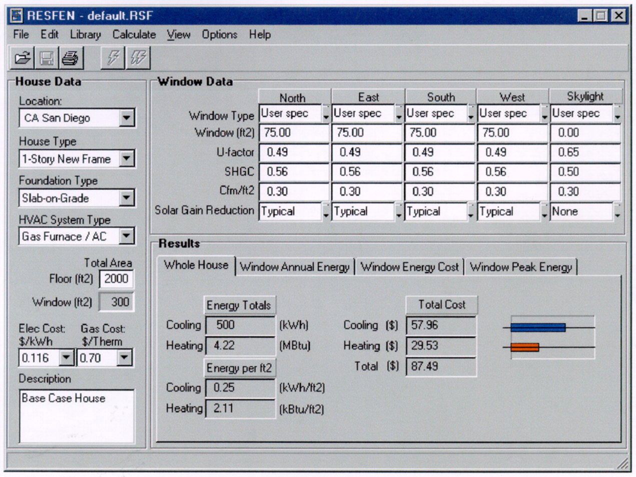

Figure 8 *Main screen of RESFEN used for analyzing fenestration product energy impacts in a typical residential building in North America.*

ing of the fenestration product properties (such as those calculated by WINDOW 4 or WINDOW5) of close to 100,000 products sold throughout the U.S.

- The Efficient Windows Collaborative (EWC) web site (www.efficientwindows.org) includes estimates of energy savings for various generic fenestration product types in 52 typical North American climates.

These existing tools all are pieces of the puzzle. Although there are some links among them (for example, WINDOW's output to RESFEN), further connections among them would permit more detailed modeling of fenestration product performance in different applications. For example, currently only some details of a fenestration product's construction that affect how it may perform in a dynamic environment are passed from WINDOW5 to RESFEN. Similarly, the NFRC CPD is a comprehensive listing of product performance data, but it does not include links to a product's dynamic performance data. The EWC web site includes detailed energy information for a variety of representative products in a variety of typical houses/climates, but it does not allow users to customize an application or product.

These missing links help define the nature of future tools. Although it is not the intent of this paper to define a blueprint for a future tool that would address all of these connections, we identify the components and functionality of such a tool.

- The tool would be applications-oriented, so a definition of a fenestration product's final application (building type, orientation, shading and other solar gain reductions, HVAC system) is critical.
- While tools such as WINDOW, which defines performance parameters for typical, "code," or "design" conditions will be necessary, these same algorithms and a full detailed description of a fenestration product will need to be tied into whole building energy analysis tools.
- Physical effects that depend on applications (such as convective heat transfer in frame cavities and glazing cavities, self-shading, and local interior film coefficients) and that are likely to play a more significant role as fenestration products become more efficient, should be treated with greater accuracy than is the norm today. An effective software tool would predict a fenestration product's surface temperature distribution at any point in time, thus providing information on comfort and condensation effects.
- A master tool would house a list of fenestration products with detailed physical descriptions such as those currently available only in programs that contain product data, such as WINDOW/THERM/Optics. This list would be available for use by other portions of the master tool.
- Output, both quantitative and qualitative, on condensation, thermal and visual comfort, UV fading, HVAC needs, and utility peak load impacts would be available in the program. Examples would include video representations of condensation patterns on a fenestration product throughout a winter or information describing where in an interior space a user might feel uncomfortable as a result of solar heat gain and when this discomfort is likely to occur (season, time of day, etc.).

A great deal of technical work will be required to develop a tool capable of addressing the details identified above. A key potential effect on the fenestration product industry would result from the tool's ability to aid in custom selection of specific products for specific applications. Many manufacturers currently find cost efficiencies in developing a "one size fits all product," particularly for residential applications. If savings from installing different fenestration products on different orientations of the same building are to be realized, this process will have to change. We contend that, in the era of the Internet, fenestration product ordering and delivery have already become more customized and trackable. The software described above will facilitate appropriate installation of efficient products to maximize the energy savings they can achieve. Although installation is primarily the responsibility of contractors, it is quite possible that, if fenestration products are ordered properly based on detailed information about their performance in specific applications, they will "know" where they are to be installed when they arrive at the site.

CONCLUSIONS

Improving software for the analysis of fenestration product energy efficiency and developing related information technology products that aid in optimizing the use of fenestration products for energy efficiency are essential steps toward ensuring that more efficient products are developed and that existing and emerging products are utilized in the applications where they will produce the greatest energy savings.

Given the diversity of building types and designs and the climates in the U.S., no one fenestration product or set of properties is optimal for all applications. Future tools and procedures to analyze fenestration product energy efficiency will need to both accurately analyze fenestration product performance under a specific set of conditions and look at whole fenestration product energy performance over the course of a yearly cycle and in the context of whole buildings.

Several steps have already been taken toward creating fenestration product software that will provide the information necessary to determine which details of a fenestration product's design can be improved to have the greatest impact on energy efficiency, what effects changes in fenestration product design will have on the comfort parameters that are important to consumers, and how specific fenestration product designs will perform in specific applications. Much work remains to be done, but the energy savings potential justifies the effort. Information is relatively cheap compared to manufacturing. Information technology has already been responsible for many improvements in the global economy—it can similarly facilitate many improvements in fenestration product energy efficiency.

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