DEMONSTRATION OF NEW ESP-R CAPABILITY FOR QUANTIFYING THE ENERGY SAVINGS POTENTIAL OF WINDOW SHADING DEVICES

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ABSTRACT

Buildings with highly glazed facades and well insulated, air-tight envelopes result in interior spaces that are highly sensitive to solar gain. Solar gain through glazing is the largest and most variable gain in buildings and has major implications on energy consumption and peak cooling loads. The peak electricity demand in Ontario, for example, is dominated by space cooling of residential and commercial buildings. The appropriate use of window shading devices can reduce cooling energy consumption and substantially lower the peak cooling load. The potential for reducing the electricity demand on peak summer days is especially significant as the cost to construct and maintain the power distribution grid and generating capacity is directly related to the peak demand.

Recently, new capabilities for modeling windows with shading devices were incorporated into ESP-r. The work is based on a set of shading models, designated the ASHWAT (ASHRAE Window Attachment) models, which were developed with emphasis on generality and computational efficiency. Measurements performed at the National Solar Test Facility (NSTF) on a full scale window with various shading attachments were compared to calculated values predicted by the ASHWAT models. The predicted results aligned well with measured data, giving confidence to the applicability of the models.

To demonstrate the new modeling capability within ESP-r, simulation examples illustrating the impact of different shading configurations on cooling energy, peak load and thermal comfort are presented. In particular, a simulation of an automated external shading system highlights the role of shading on the energy performance of a solar house design entered into the Solar Decathlon 2009 competition. The external shading design is compared with other options including a solar protective coating on the outside glass as well as indoor shades. Simulations were also carried out to illustrate the impact of shading devices on winter nighttime heat loss and thermal comfort. Finally, a general procedure for using the shading models within ESP-r is outlined, highlighting straightforward user input by means of a user-friendly graphical interface.

INTRODUCTION

Solar gain through glazing is the largest and most variable gain and has major implications on energy consumption and peak cooling loads. The peak electricity demand in Ontario, for example, is dominated by space cooling of residential and commercial buildings. The appropriate use of window shading devices can reduce cooling energy consumption and substantially lower the peak cooling load. The potential for reducing the electricity demand on peak summer days is especially significant as the cost to construct and maintain the power distribution grid and generating capacity is directly related to the peak demand.

The shift toward better insulated and air-tight building envelopes, combined with the architectural trend of highly glazed facades, is resulting in new buildings that are even more sensitive to solar gain. With improved window technology and economies of scale it is now possible to build affordable homes that successfully utilize passive solar heating via large south facing glazing without compromising winter night-time comfort and excessive heat loss. However, without appropriate solar gain control strategies, building peak cooling loads, increased cooling energy and occupant discomfort can offset any benefit from thermally benign envelopes and passive solar heating. Control of solar gain is not only necessary in current highly glazed, poorly insulated buildings, but is critical in the design of new energy efficient residential and commercial green buildings.

Shading devices such as operable louver blinds, roller blinds, drapes, overhangs, and retractable awnings are simple and effective devices, yet their impact on peak cooling loads and annual energy consumption is poorly understood. Until recently, the impact of shading devices has been generally neglected in envelope design and equipment sizing. Few tools exist that can aid the building designer in quantifying the impact of window shading on building loads.

With the renewed impetus toward energy efficiency in building design, the potential benefits of automated switchable shades are significant, and the ability to appraise the impact of such technologies is in demand. There is a clear need for an explicit treatment of window shading layers in building energy simulation. Control schemes for automated shades can be readily integrated with simulation, achieving fine resolution of solar gain control to determine the resulting impact on thermal loads, electrical lighting power and luminance levels.

In order to bridge the gap between research and design practice, such models require practical, straightforward approaches to be successfully deployed, but need to adequately represent real-world complexity. This paper presents a simulation tool for the asessment of window shading strategies on building performance that attempts to adhere to these principles. A graphical interface is aimed at quick synthesis of complex fenestration assemblies. The underlying complex fenestration models, linked with ESP-r, resolve the complexities of energy transport interactions between glazing/shading systems and the building thermal domain. Simulation examples are presented to demonstrate the capabilities of the complex fenestration facility.

BACKGROUND

Model Development

The energy performance of windows with shading devices was modeled using a two step procedure, considering the center-of-glass region of the window only. Solar radiation was considered in the first step by developing a multi-layer solar optical model for glazing/shading systems. This newly developed model is an extension of an existing model for systems of specular glazing layers and includes the effect of layers that create scattered, specifically diffuse, radiation in reflection and/or transmission (Wright and Kotey 2006). The multi-layer solar optical model estimates the system solar transmission and absorbed solar components. The absorbed solar components appear as energy source terms in the second step – the heat transfer analysis. A multi-layer heat transfer model for glazing/shading systems was subsequently developed to solve energy balance equations at each layer (Wright 2008). The simultaneous solution of the energy balance equations yields the temperature as well as the convective and radiative fluxes.

Solar and longwave property sub-models that serve as input to the multi-layer models were developed for four specific types of window attachments, i.e., drapes, venetian blinds, roller blinds and insect screens (Barnaby et al. 2009). In order to retain generality and practicality while striking a balance between complexity and computational speed a simplified approach was taken regarding the way in which radiation interacts with a shading layer. Two points are worth mentioning:

- Shading layers are characterized by making the assumption that each layer, whether homogeneous or not, can be represented by an equivalent homogenous layer that is assigned spatially-averaged "effective" optical properties.
- Some portion of the incident solar radiation passes undisturbed through openings in a shading layer and the remaining portion is intercepted by the structure of the layer. The structure may consist of yarn, slats, or some other material. The portion of the intercepted radiation that is not absorbed will be scattered and will leave the layer as an apparent reflection or transmission. These scattered components are assumed to be uniformly diffuse. In addition, a shading layer will generally transmit longwave radiation (i.e., it is diathermanous), by virtue of its openness, and effective longwave properties are assigned accordingly.

Using effective optical properties and a beam/diffuse split of solar radiation at each layer, the framework used to represent multi-layer systems provides virtually unlimited freedom to consider different types of shading layers. This framework also delivers the computational speed needed in the context of building energy simulation.

A comprehensive fenestration model, designated ASHWAT (ASHRAE Window Attachment) was developed to handle the calculation of the energy performance of windows with shading devices (Wright et al. 2009). The ASHWAT formulation provides significant convenience and generality in the characterization of individual shading layers. Few optical data are needed to characterize a particular layer and many options can easily be considered. These benefits are obtained by using models, based on a small set of subcomponent characteristics, to calculate effective layer properties instead of relying on empirical information about the entire layer. For example, the effective solar optical properties of a venetian blind can be calculated as a function of slat geometry and solar properties of the slats. The only input data needed to fully characterize drapery fabric, roller blinds and insect screens are openness, total solar transmission and total solar reflection (all measured at normal incidence).

Solar and longwave radiation models were created for all layer types, based on a combination of original research and fundamental principles. Methods to obtain convective heat transfer coefficients for glazing cavities are well established.

The convective heat transfer coefficients in the vicinity of a shading layer attached next to a glazing system are specified by the calling routine (i.e., the building simulation program). Certain values might be chosen to match similar situations modeled elsewhere in the building simulation or they might be specified to differentiate between natural and forced convection and perhaps between different types of forced convection caused by different types of diffusers. Established values are available in the limiting cases where the shading layer is spaced well away from the window or where the spacing approaches zero. Knowing these limits a model has been formulated to make a smooth transition so the user can place the shading layer at any distance from the surface of the window (Wright et al. 2009).

Model Validation

Experiments were perfomed using one insulated glazing unit (IGU) in combination with various shading attachments, each system being installed in an indoor solar simulator – the National Solar Test Facility (NSTF). The data collected consist primarily of solar gain (i.e., SHGC) and solar transmission. The IGU used in each case was a conventional double glazed (CDG) unit consisting of two sheets of clear (3 mm) glass separated by a 1/2 inch air-filled cavity. The IGU was commercially produced. Foam, warm-edge edge-seals were used. The shading attachments included all four shading layer types described by the ASHWAT models. Simulations were completed to reproduce the conditions for every experiment and comparisons between NSTF measurements and ASHWAT calculations are shown in Figure 1. Figure 1a shows very good agreement between NSTF measurements of solar transmission and the ASHWAT models. The discrepancy is less than 0.05 in all cases. The discrepancy between measured and calculated center-glass SHGC values was also small, generally less than 0.05, and a mild sensitivity was noted with respect to surface convection heat transfer coefficients. Agreement for IAC results (Figure 1b) was also very good. A detailed description of the experimental procedure can be found in (Kotey et al. 2009).

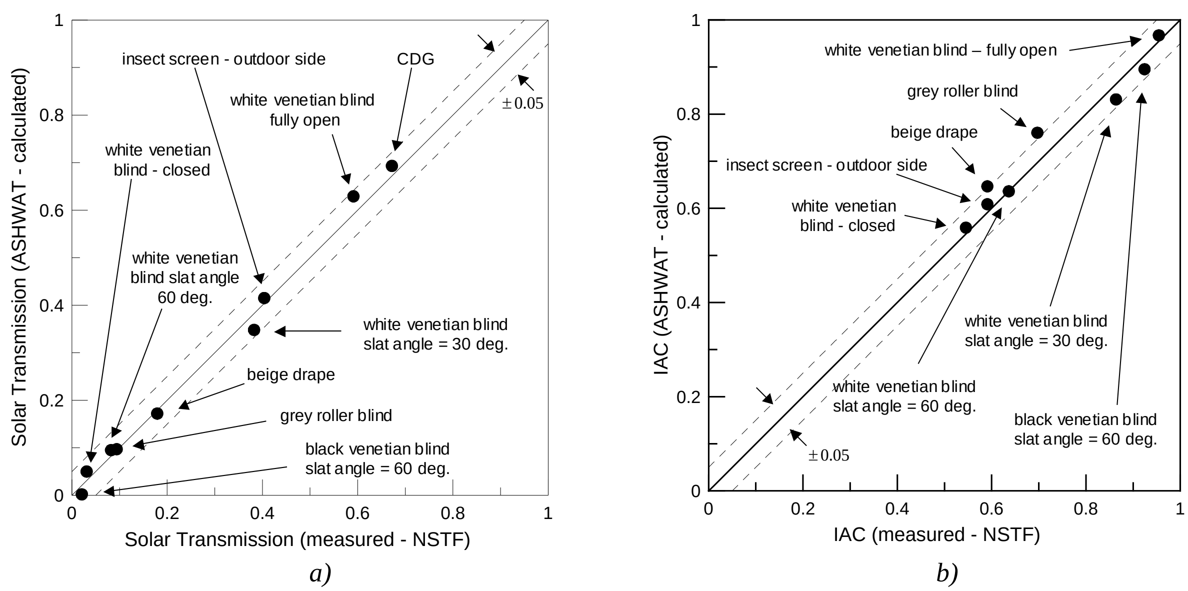


Figure 1: ASHWAT vs. NSTF Comparison of centre-glass a) solar transmittance and b) IAC at normal incidence for various shading layers attached to conventional double glazed window.

ESP-R IMPLEMENTATION

Description of ESP-r

ESP-r is a general purpose integrated building simulation software environment which attempts to capture the dynamic behaviour and interaction of building systems, encompassing the modeling of multi-zone building thermal domains, inter-zone air flow, intra-zone air movement, HVAC systems and electrical power flow. The software has been in development since the 1970s and is made available at no cost under an open source license. ESP-r is based on a design approach in which additional complexity and technical domain solvers are applied as the building description evolves. The software serves as a comprehensive platform for development and collaboration in building simulation efforts.

The finite volume heat balance method is used in ESP-r to establish an equation set describing the thermal state of discretized building systems. A simultaneous numerical solution can then be generated for such an equation set. The approach is based on applying conservation principles to each node. Thus, for any node I in a discretized system, the energy balance equates the rate of heat being stored in node I to the net rate of heat flow to node I. The theory behind ESP-r has been documented extensively in literature (e.g. Clarke 2001).

Current Treatment of Glazing and Shading

The distribution of solar radiation within a building envelope and interior surfaces is resolved in ESP-r by introducing energy generation terms to appropriate nodes. The processing of solar fluxes through transparent elements is handled in ESP-r by the transparent multi-layer construction (TMC). The TMC is an extension of the multi-layer nodal scheme used to model opaque constructions. Nodal solar absorption sources for TMC transparent layers as well as overall system transmission are determined on a time-step basis based on the sun's position.

In ESP-r a set of optical data is associated with each TMC. This set consists of system solar transmission for the entire window and absorption at each glazing layer. The properties are given for normal incidence and 5 off-normal incidence angles. The TMC off-normal properties corresponding to the solar incidence angle at each time step are determined by interpolating the given optical data. Standard optical property sets are included in the ESP-r optical database. The user can also define a custom property set or import data from third party software such as WINDOW 5. Solar gain control may be achieved by manipulating the optical property sets of a TMC for prescribed control periods. At run-time, the default optical set is used in the simulation until the specified control period is reached, for which the replacement optical set is then invoked. This strategy relies on prior knowledge of the optical properties for a specific window/blind configuration, and therefore relies on third party software or manual input of all the properties by the user. In addition, optical data sets for TMCs are assumed to be rotationally symmetric and cannot cope with rotational asymmetry introduced by, for example, a slat-type shading layer.

Currently, ESP-r treats heat transfer across air gaps via a single resistor representative of the convective and longwave radiative heat transfer for a prescribed design condition. This gap resistance can be tuned to represent various fill gases and glazing coatings but this approach relies heavily on specific knowledge of the window U-value. Edge and frame effects can also be modeled by adjusting the gap resistances. In reality, the total resistance in a window cavity is temperature dependent. The convective heat transfer coefficient is dependent on the glazing temperatures. Longwave radiation fluxes have a fourth order temperature dependency.

The Complex Fenestration Construction (CFC)

The fundamental strategy for the implementation of the ASHWAT shading models is the design of a new multi-layer construction within ESP-r, the complex fenestration construction (CFC). The CFC type utilizes the ESP-r multi-layer nodal scheme, with provisions to cope with additional shading layer complexities such as: scattering of solar beam energy by non-specular shade materials, the semi-transparent nature of shades to long-wave radiation (i.e. diathermanous), and convective air-flow between shade and glazing layers.

Only slat-type blind models are currently implemented in the CFC type, however, the framework is general enough for the addition of other types of shading layers. The CFC type can be applied to vertical external surfaces in ESP-r and can be used to model windows with or without shading devices.

The main advantage of the CFC solar and thermal processing routines over the existing ESP-r TMC type is in the way the properties of glazing/shading layers are characterized. Each glazing/shading layer is treated explicitly and the corresponding layer properties, including solar optical, longwave radiative and fill gas properties, are determined at each simulation time-step. With such a framework in place, the control of individual layer properties (e.g., slat angle of a blind) at the time-step level becomes straight forward. The CFC thus introduces the ability for simulating dynamic control of solar gain through fenestration without cumbersome input requirements such as alternate optical propety sets. Alternate property sets currently used for TMC control are difficult to establish, especially if the system includes a shading layer. The position of the shading layer (e.g., indoor/outdoor/between-the-glass) has a significant impact on the distribution of absorbed solar fluxes. Thus, an improper set of alternate optical properties has major implications on the portion of solar energy flowing inward to the zone.

Details on the implementation of the complex fenestration construction into ESP-r are documented in (Lomanowski 2008).

Graphical Front End

To reduce the input burden on the user, a simple graphical user interface tool, the Glazing Shading Editor (GSLEdit), has been developed at the Advanced Glazing Systems Laboratory (Wright et al. 2009). The editor was designed for quick synthesis of a glazing product with or without shading components. The editor compiles system information into an organized output file. When a CFC is specified in ESP-r, the GSLEdit file is imported to automatically generate the inputs necessary to describe the CFC composition. System composition in GSLEdit is based on access to glazing and shading layer databases. Figure 2 summarizes the utilization of CFCs in ESP-r model generation.

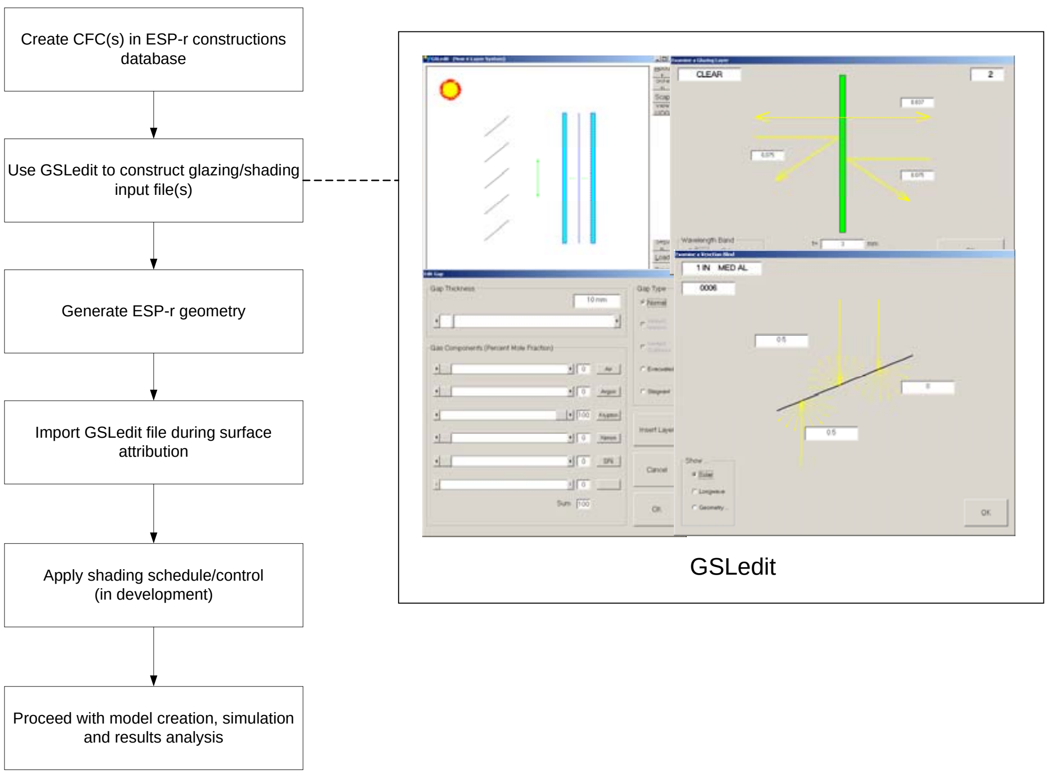


Figure 2: General procedure for adding CFCs to an ESP-r model.

CFC CAPABILITIES – SIMULATION EXAMPLES

The development of the CFC facility in ESP-r coincided with design efforts initiated for delivery of the North House entry into the 2009 Solar Decathlon (US DOE Solar Decathlon 2009), prepared by a multi-faceted team from the University of Waterloo, Ryerson University and Simon Fraser University (Team North 2009). The design narrative behind the North House emphasizes a highly glazed façade which connects the occupants to their environment, and maximizes the use of passive solar heating. North House engineering team members were thus faced with the challenge of preserving the architectural merits of the design while ensuring that optimal performance and occupant comfort are met. A responsive envelope is a key aspect of the design, providing solar protection and solar utilization when needed. The North House design offered an excellent opportunity to explore the new ESP-r complex fenestration facility. It is worth mentioning that a successful passive solar design must exhibit a balance between envelope design variables such as window to wall ratio, orientation, glazing SHGC, U-Value, solar transmisson and the amount of thermal mass and its distribution. Given the large percent glazing area of the North House, this design is not necessarily an optimal solution in this regard; rather, it is an exercise in combining cutting edge architecture with the state of the art in window and framing technology to serve as a demonstration project and research platform.

Based on early simulation work for the North House team, this section demonstrates how the complex fenestration construction models can be useful in selecting a glazing façade. The scope of the analysis is limited to considering different glazing façade compositions within a constrained house geometry, percent glazing area and thermal mass distribution.

Simulation Methodology

Figure 3 illustrates a basic ESP-r abstraction of the North House geometry. The south facing façade is composed of glazing entirely, and half of the east and west façade areas are also composed of glazing. The opaque sections are highly insulated, to about R50, and the floor is lined with a phase change material (PCM) to provide thermal mass. For simplicity, and to isolate for the effects of façade alone, constant ventilation of 0.2 ACH was applied to the interior zone, without any internal gains or occupant schedules. The glazing façade is a quad glazing system in which the two intermediate layers between the inner and outer glass layers are suspended low-e coated films. The glazing cavities are filled with krypton gas. The resultant center-of-glass performance indices calculated in Window 5 are: U-Value = 0.486 W/m^2K (~R12), SHGC = 0.44, solar transmittance T_{sol} = 0.31 and visual transmittance T_{vis} = 0.59. Edge and frame effects were ignored in the model. Idealized thermostatic air based heating and cooling was applied to maintain the zone air temperature between 22 and 24˚C. A climate file based on CWEC data for Toronto, Canada, was used. ESP-r's Insolation and Shading module was employed to determine the monthly internal solar distribution.

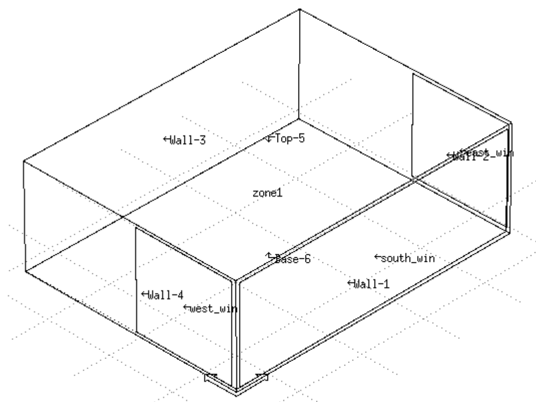


Figure 3: ESP-r model geometry based on the North House design.

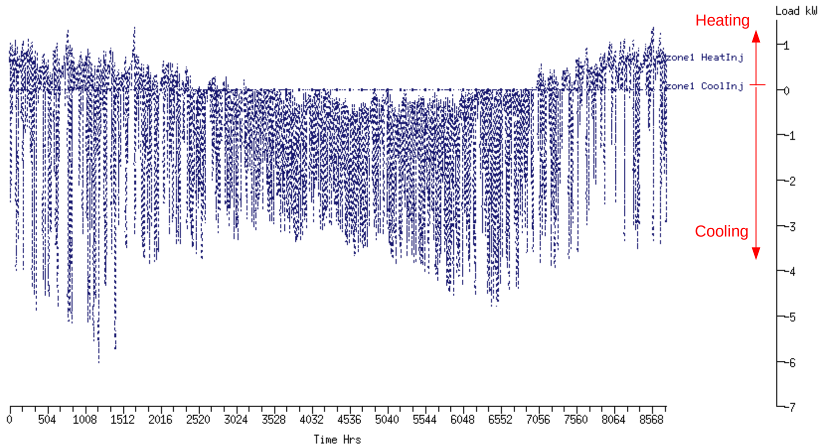
Peak Load and Energy Assessment

Appraising the impact of glazing façade design on annual energy and peak load performance is the main application of the complex fenestration construction. Figure 4 shows hourly idealized heating and cooling loads for an annual simulation for two cases: a) quad glazing façade without shading and b) quad glazing façade with automated outdoor slat-type shades. The automated shading system is based on a thermostatically controlled algorithm that closes the slats to 60˚ from horizontal if the zone air temperature rises above 24˚C, and otherwise adjusts the slat angle to a parallel position with the sun's profile angle, thereby allowing for maximum transmission.

It is clear from Figure 4a that the house is hypersensitive to solar gains and will overheat routinely without any solar protection. It is interesting to note that the maximum cooling peaks are observed in the winter months when the sun is low in the sky, as well as in late summer/early fall when the sun is relatively low and outdoor temperatures are still high. The addition of an idealized dynamic shading system eliminates almost entirely the need for sensible cooling, as is evident from Figure 4b. However, in reality, the shading system will function not only to minimize solar gains but also to provide view, daylight and glare control. Therefore a compromise between these four functions would most likely result in higher solar gains than in the idealized condition. In addition, internal gains and latent loads must be considered in the design of the cooling system.

The North House features super-insulated walls/floor/ceiling, an air-tight envelope and large south facing glazing with a high SHGC. Although this design is extreme, the simulation results demonstrate the large impact of solar gain in buildings with thermally benign envelopes and large glazing areas. Moreover, the significance of outdoor shading in such designs is clear. It is worth noting that a spectrally selective solar protective coating on the glazing façade could achieve similar reductions in cooling. However, the SHGC of such a glazing would have to be below 0.15 to achieve such a reduction. With such low SHGC, the visual transmittance suffers, and more importantly, the capacity for passive solar heating diminishes.

Figure 5 integrates the hourly idealized heating and cooling loads to show the annual idealized heating and cooling energy for four façade designs: quad glazing without shading, quad glazing with outdoor automated shades, quad glazing with indoor automated shades and quad glazing with solar protective coating (SHGC=0.15).



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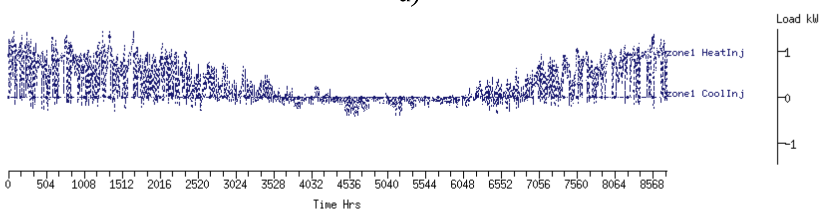


b)

Figure 4: Annual idealized cooling and heating load profile: a) without shading, b) with outdoor automated slat-type shades.

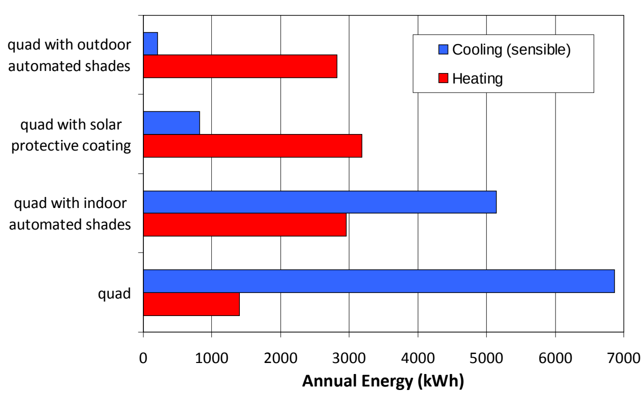


Figure 5: Annual heating and cooling energy for various façade designs.

The lowest heating energy and highest cooling energy occurs for the high SHGC quad glazing. In this scenario, the thermal mass is always charging during sunny periods even though the zone air is being cooled. It is not surprising that the highest total energy consumption occurs for the façade with an automated indoor shade. The indoor shade absorbs solar energy and due to its minimal thermal mass, readily releases the heat to the zone air via convection. This results in rapid overheating and causes the shades to close more often, preventing the sun's rays from charging the thermally massive floor and, moreover, causes the shades to absorb even more solar radiation. The results indicate that a quad glazing with a solar protective coating (SHGC=0.15) performs almost as well as the façade with outdoor shades. This indicates that with the high SHGC quad glazing (SHGC=0.44), the house reaches the cooling setpoint quickly during sunny periods, even with the thermally massive floor. As a result, the outdoor shades are often closed during sunny winter days. It is worth noting that the façade with outdoor shades can be optimized to further drive down the heating energy by, for example, using an economizer to increase the ventilation rate during sunny periods to flush out the warm zone air. As a consequence, the thermal mass can be charged for longer periods, harnessing more solar energy, while maintaining occupant comfort. Another possibility is to increase the cooling setpoint and/or to add more thermal mass or phase change material.

Figure 6 presents simulation results for a 24 hour snapshot for different glazing façade options. The simulation period is a summer day in late August, with mild ambient temperatures and high solar radiation (direct normal radiation peaks at 900 W/m^2). For the façade options with shades, the slat angle is 60˚ closed for the duration. The total solar transmitted flux is shown on the positive y-axis. The zone idealized cooling load, convective and longwave radiative fluxes are shown on the negative y-axis. The convective and longwave radiation fluxes are the glazing façade indoor surface fluxes multiplied by the total glazing area plus shade area for cases in which shades are present.

The results in Figure 6 show relatively low solar transmitted fluxes for all three cases, as a consequence of the presence of shades for cases a) and c) and the solar protective coating for case b). The convective and longwave radiation curves indicate that the outdoor shade layer offers maximum protection from solar gain. The quad glazing with the solar protective coating cuts out most of the gain, but the glazing layers also absorb more solar energy which ends up in the indoor space as convective and longwave radiative flux. In the case of an indoor shade, it is clear that the cooling load is almost entirely attributed to the convective load from the combination of shade and indoor glazing surfaces.

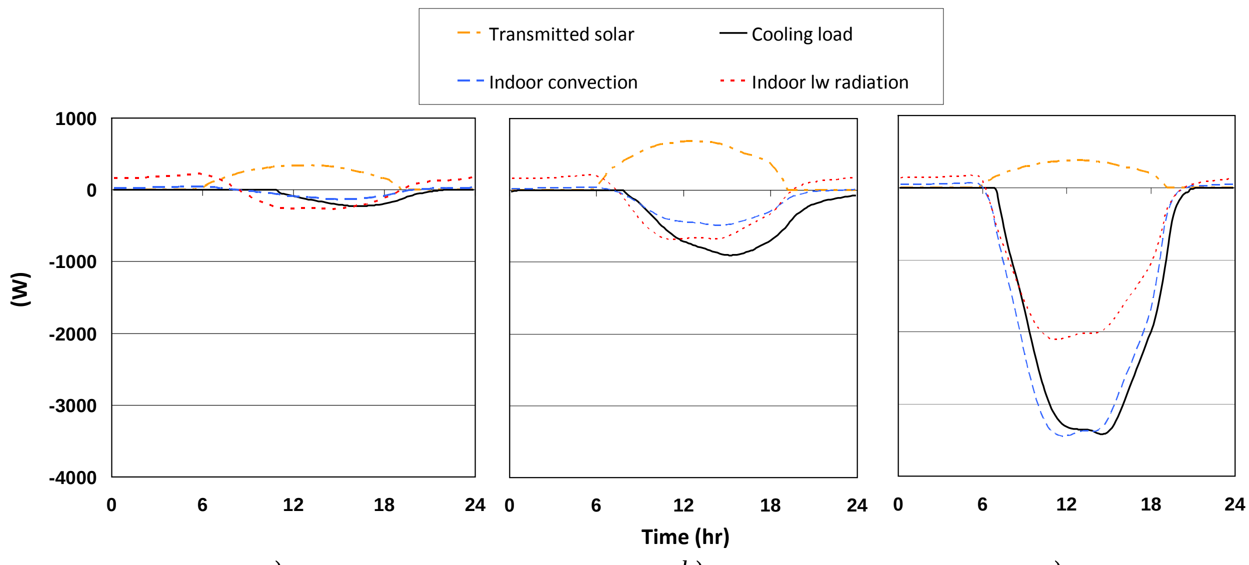


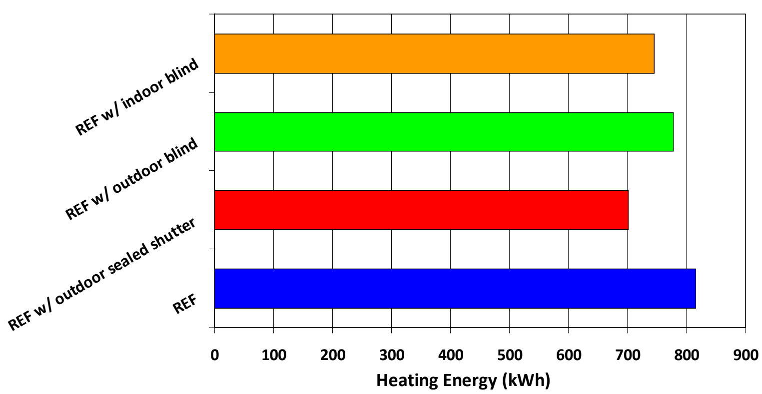
Figure 6: Zone loads for 24 hour summer day simulation period. a) with outdoor shade – slats at 60˚ b) with solar protective coating and c) with indoor shade – slats at 60˚.

Window Heat Loss and Thermal Comfort

Complex fenestration constructions are fully integrated into ESP-r's nodal network. Thus, any of the nodes may be interrogated for temperature and heat fluxes via ESP-r's results analysis tools. Such information is particularly useful for appraising thermal comfort and heat loss through the center-of-glass glazing region. For the following illustrative example, the quad glazing façade in the simulation model geometry was replaced with a common double glazing with low-e and argon (U-Value =1.482 W/m^{2}K). A simulation period from January 1 – 15 was chosen for this example. In addition, solar processing in ESP-r was turned off to simulate constant night-time conditions for the duration of the two week period. Figure 7a shows the resultant heating energy for the two week period given four different glazing options: the reference double glazing, double glazing with outdoor sealed shutter, double glazing with outdoor free hanging blind (slats closed) and double glazing with indoor free hanging blind (slats closed). Figure 7b shows the corresponding south glazing center-of-glass inside glass surface temperatures for the four glazing façade options. For the case with indoor shade, the shade temperature is also given. The sealed shutter was modeled as an additional glass pane on the outside. This is an idealized condition which prevents any aiflow between the outside and the cavity between the shutter and outside glazing surface. Such an airtight shutter is not realistic but serves the purpose of presenting the best case scenario.

It is evident from Figure 7a that some energy savings are achieved by adding a shading layer to the glazing facade. The idealized outdoor shutter case results in the highest energy savings of about 15%. It is important to remember that these values reflect a house geometry with a very large glazing area and are probably not reflective of typical dwellings in which the window to wall ratio is much lower.

The indoor glazing surface temperatures shown in Figure 7b indicate only a marginal increase in temperature for a window with an outdoor free-hanging blind and about a 1.5˚C increase for the outdoor sealed shutter case. The temperature of the indoor blind is significantly higher than the reference indoor glazing surface since the blind is immersed in the zone air. Heat loss from the indoor blind occurs mostly via longwave radiation to the colder innermost glazing surface. In the presence of an indoor blind, the innermost glazing surface no longer sees the warm room temperature walls, instead longwave exchange occurs with the indoor blind which reaches a lower steady-state temperature. Combined with a lower convective heat transfer rate at the innermost glazing surface due to the presence of the indoor blind, the glass temperature is observed to decrease by about 2˚C compared to the reference case. These results indicate that placing an indoor blind may reduce the indoor glass temperature below its dew point and may lead to condensation problems, especially if the blind is placed close to the window.



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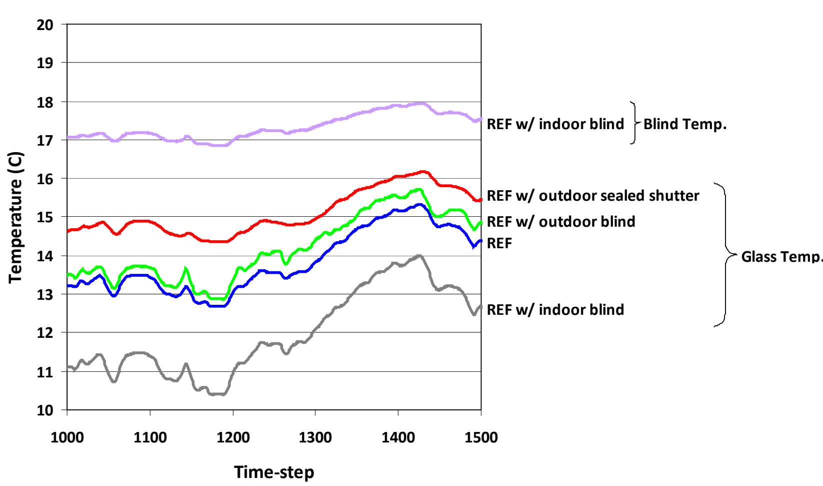

b)

Figure 7: Heating energy and inside surface glazing temperatures for a two-week winter night-time simulation period with different fenestration compositions.

FURTHER DEVELOPMENT

Work is ongoing to extend the ESP-r complex fenestration facility to include shading scheduling and control strategies as well as the treatment of other shading layers such as drapes, roller blinds and screens. It is recommended that the complex fenestration facility also be coupled with daylighting models in ESP-r, extending the capability for appraising lighting control strategies for the optimization of cooling energy and lighting electrical energy consumption.

CONCLUSIONS

The successful implementation of the ASHWAT shading models into ESP-r in the form of the complex fenestration construction has been demonstrated. The tool was developed with emphasis on glazing/shading system generality to allow for specification of any combination of shading/glazing layers. The generation of input files for CFC types relies on straightforward composition of input parameters via a graphical user interface, the Glazing Shading Layer editor GSLedit.

Simulation examples based on the design of the North House demonstrate how the complex fenestration facility can be used in practice to appraise the impact of glazing/shading compositions on building performance. In particular, the simulations highlight the importance of external shading for solar protection of highly glazed facades and quantify the impact of glazing façade composition on cooling peak loads, cooling energy and thermal comfort.

ACKNOWLEDGEMENTS

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