Methodology for selecting fenestration systems in heating dominated climates

Bastien, Diane; Athienitis, Andreas K.

Published in:
Applied Energy

DOI:
10.1016/j.apenergy.2015.05.083

Publication date:
2015

Document version:
Submitted manuscript

Methodology for selecting fenestration systems in heating dominated climates

Diane Bastien*, Andreas K. Athienitis

Dept. of Building, Civil and Environmental Engineering, Concordia University, 1455 Maisonneuve W., Montreal, Quebec, Canada H3G 1M8

Abstract

Selecting optimum windows in heating dominated climates is a complex task because of the inherent trade-off between their U-value and solar heat gain coefficient. In addition, the use of shades is known to reduce heat losses, but they are rarely selected for this intent and considered as an integrated fenestration system at the design stage. This paper presents a method for selecting optimum fenestration systems (windows with shades) to maximize the annual net energy balance. The method has the capability to simulate a one or two layer shading system with one exterior and/or one interior planar shade(s). This methodology generates 2D schematics indicating the net energy balance of different fenestration systems. Such schematics are useful at an early design stage when there is a need to compare different design options for different orientations on a relative basis.

Diagrams are presented for five glazings with an interior roller shade, an exterior roller shutter and a combination of both, for the four cardinal orientations for the city of Montreal, Canada. A comparison of simulated and experimental U-values of four shading devices indicates results reasonably close to each other.

Key words: windows, shading device, thermal screen, heat losses, solar gains, sunspace

*Corresponding author +1 514 848-2424 #7080

Email addresses: solarbuildings@dianebastien.ca (Diane Bastien), aathieni@encs.concordia.ca (Andreas K. Athienitis)

Nomenclature

A	Total building envelope area, m^2
A_f	Frame area, m^2
A_{floor}	Conditioned floor area of building, m^2
A_g	Glazing area, m^2
A_i	Area of surface i, m^2
A_t	Total window area, m^2
D	Yearly heat load, kKh
DNR	Direct normal radiation, kW/m^2
f_j	Correction factor for diffuse radiation
$F_{i,g}$	View factor between surface i and the ground
F_s	Shading factor
g_j	Angular profile
GHR	Global horizontal radiation, kW/m^2
$h_{c,ext}$	Exterior convective heat transfer coefficient, $W/(m^2K)$
$h_{c,int}$	Interior convective heat transfer coefficient, $W/(m^2K)$
$h_{c,nv}$	Convective coefficient in a non vented cavity, $W/(m^2K)$
$h_{c,v}$	Convective coefficient in a ventilated cavity, $W/(m^2K)$
h_{ext}	Combined exterior heat transfer coefficient, $W/(m^2K)$
h_{int}	Combined interior heat transfer coefficient, $W/(m^2K)$
h_r	Radiative coefficient in the window/shade cavity, $W/(m^2K)$
$h_{r,ext}$	Exterior radiative heat transfer coefficient, $W/(m^2K)$
$h_{r,int}$	Interior radiative heat transfer coefficient, $W/(m^2K)$
h_{ExtS}	Combined coefficient in ext shade/window cavity, $W/(m^2K)$
h_{IntS}	Combined coefficient in int shade/window cavity, $W/(m^2K)$
H_g	Height of glazing, m
I	Corrected incident radiation, kWh/m^2
I_b	Incident beam solar radiation, kW/m^2
I_d	Total incident diffuse solar radiation, kW/m^2
I_{dg}	Ground diffuse solar radiation incident on a surface, kW/m^2
I_{ds}	Sky diffuse solar radiation incident on a surface, kW/m^2
$I_{ds,ho}$	Horizontal sky diffuse solar radiation, kW/m^2
l_Ψ	Vision area perimeter, m
j	Number of panes
k	Thermal conductivity of air, W/(mK)
N_{oc}	Number of occupants

Nu	Nusselt number
OP	Openness factor
q	Internal gains, W
Q	Net energy gain (or loss), kWh/m^2
Q'_t	Energy gain (or loss) at time t, kWh/m^2
R_{ExtS}	Thermal resistance of exterior shade, m^2K/W
R_{IntS}	Thermal resistance of interior shade, m^2K/W
$SHGC_g$	Solar heat gain coefficient of glazing
$SHGC_{gS}$	Solar heat gain coefficient of covered glazing
$SHGC_w$	Solar heat gain coefficient of window
$SHGC_{wS}$	Solar heat gain coefficient of covered window
$SHGC_{xxxS}$	SHGC of glazing with interior and/or exterior shade
t	Time, h
T_b	Balance temperature, °C
T_i	Interior temperature, °C
T_i^*	Standard interior temperature, °C
T_o	Outdoor temperature, °C
T_o^*	Standard exterior temperature, °C
$T_{s,i}$	Temperature of the interior surface of the shade, °C
$T_{s,o}$	Temperature of the exterior surface of the shade, °C
$T_{w,i}$	Temperature of the innermost glazing, °C
$T_{w,o}$	Temperature of the outermost glazing, °C
U	Overall building U-value, including infiltration, $W/(m^2K)$
U'_t	U-value of fenestration system at a time t $W/(m^2K)$
U_{eff}	Effective U-value, $W/(m^2K)$
U_{ExtS}	Overall U-value of glazing with exterior shade, $W/(m^2K)$
U_f	Frame U-value, $W/(m^2K)$
U_g	Glazing U-value, $W/(m^2K)$
U_{gs}	Shaded glazing U-value, $W/(m^2K)$
U_{IntS}	Overall U-value of glazing with interior shade, $W/(m^2K)$
$U_{IntExtS}$	Overall U-value of glazing with int and ext shade, $W/(m^2K)$
U_w	Window U-value, $W/(m^2K)$
U_{wS}	Shaded window U-value, $W/(m^2K)$
$U'_{\text{øh}_{ext}}$	Glazing U-value without h_{ext}, $W/(m^2K)$
$U'_{\text{øh}_{int}}$	Glazing U-value without h_{int}, $W/(m^2K)$
$U'_{\text{øh}_{ext}\&\text{h}_{int}}$	Glazing U-value without h_{ext} and h_{int}, $W/(m^2K)$
v	Mean air velocity in the cavity, m/s

α_s	Shade absorptance
α_{gi}	Absorptance of ith pane of glass
$\epsilon_{s,i}$	Emissivity of the interior surface of the shade
$\epsilon_{s,o}$	Emissivity of the exterior surface of the shade
$\epsilon_{w,i}$	Emissivity of the innermost glazing
$\epsilon_{w,o}$	Emissivity of the outermost glazing
η	Utilization factor
ρ_{gr}	Ground reflectivity
ρ_g	Glazing reflectivity of outer pane
ρ'_g	Glazing reflectivity of inner pane
ρ_s	Shade reflectivity of exterior surface
ρ'_s	Shade reflectivity of interior surface
Ψ	Linear thermal transmittance, W/(mK)
θ	Incidence angle, $^\circ$
τ_{xxxS}	Transmittance of glazing with interior and/or exterior shade
τ_s	Shade transmittance
τ_g	Glazing transmittance
σ	Stefan Boltzmann constant, W/(m^{-2}K^{-4})

1. Introduction

With increasing awareness to climate change and sustainable development, many studies have been conducted on improving the energy efficiency of buildings due to their important energy consumption. Indeed, in Canada, the energy consumed by the residential and commercial sectors represented 29% of the total energy use in 2012 [1], most of which used by buildings.

Virtually all previous research agree on the importance of windows and shading systems on the energy consumption of buildings [2, 3, 4, 5, 6, 7]. For instance, a Canadian study on high-rise residential buildings has reported that windows were responsible for an average of 31% of total energy loss [8].

Selecting optimal windows is more complicated than opaque envelope components since the performance of windows is governed by two major variables: the solar heat gain coefficient (SHGC) and the thermal resistance. In cold climates, it is desirable to have windows with both high thermal resistance and SHGC so as to optimize utilization of solar gains. The resistance of a window may be increased by adding a supplementary pane of glass, applying a low emissivity coating and using an inert gas such as argon or krypton in the cavity. However, the former two options also reduce the SHGC, which could lead to an increased heating demand. In addition, windows are one the most expensive component in a house (on a unit area basis). As a result, the selection of windows (and their area) is one of the most problematic aspect of Net-Zero Energy Buildings [9].

Windows with different orientations are not affected by these two variables to the same extent: an equatorial-facing window (referred to as south facing in the rest of the paper) will have a better performance with a high SHGC while it is more beneficial for a north window to have a lower U-value [10]. Thus selecting different windows for different orientations could reduce the energy consumption of buildings.

Moreover, the use of shading devices, and their operation if moveable, affects the performance of windows, altering their thermal performance and solar gains. An extensive study of various window attachments estimated through simulations that simple shading devices like interior roller shades and exterior solar screens could improve the U-value of a double glazed low emissivity window by 3-45% and 26-39% respectively, depending on the characteristics of the shading device [11].

1.1. Background

For improving the performance of façades, it has been suggested to divide the window area into two parts: the daylighting section at the top and the view section below. Since glazing below the workplane does not contribute significantly to daylighting and is detrimental for the building energy consumption [12], this section is better opaque, thus creating a three-section façade concept as described by Tzempelikos [13] where ideally the view section provides diffuse light only. Schumman et al. [12] suggested to use high transmission glass at the upper section and lower transmission glass in the view section for controlling glare, with additional forms of solar control for both sections. Tzempelikos et al. [2] suggested to use automated venetian blinds for the upper part and manually controlled roller shade for the lower part of the window for high daylight autonomy and comfort and low energy consumption.

As noted by Tzempelikos and Athienitis [14], cooling may be important in perimeter zones even in heating dominated climates, indicating that shading is a necessity. Because of the importance of shading devices on the performance of buildings, a few general recommendations will be reported here. For additional guidelines regarding shading strategies, one may refer to Schumman et al. [12].

Shading type and properties should vary with orientation, since their performance indices are very sensitive to this variable [14].

Exterior shading is more effective than interior shading for blocking solar gains. Interior shading devices should be light-coloured to better reflect solar radiation. For exterior shading devices, horizontal forms should be preferred for a south façade, such as overhangs and awnings, while vertical forms should be preferred for a east, west and north façades, such as vertical fins. It is also good practice to have different shading solutions that can be managed independently for the view and daylight sections [12].

Ochoa et al. [3] have found that east and west windows have the highest energy consumption, Lee et al. [4] have noted that the energy performance of east and west windows being more sensitive to changes in SHGC and visible transmittance and Huang et al. [6] have identified east and west orientations as having the most potential for reducing the energy consumption of a building using shading devices. These observations indicate that special care must be taken when designing east and west windows and their protections.

Nielsen et al. [15] noted that north windows with no shadings or fixed shadings are a relevant alternative, but suggests the use of automated venetian blinds for improving the daylight availability of large windows of other orientations.

Since shading devices play an important role in the energy performance of buildings, some tools have been developed to facilitate the task of selecting windows and window-shade systems (the latter being referred to as fenestration systems throughout this study).

1.2. Existing tools and research needs

Many tools already exist to help selecting windows and fenestration systems. Programs such as WINDOW (and its companion software THERM and RESFEN) [16, 17], WIS [18] and ParaSol [19] are stand-alone tools that calculate the solar and thermal properties of windows, which may be accompanied with some types of shading devices. WINDOW and WIS are mainly used for certification purposes as they carry out simulations at fixed conditions, usually chosen to match a specific standard. RESFEN and ParaSol offer the possibility of calculating annual heating and cooling loads associated with windows. There are also whole building energy simulation software with the capability of carrying detailed heat transfer calculations through windows and fenestration systems like EnergyPlus [20], TRNSYS [21] and ESP-r [22]. A more detailed description of these software can be found in [23], [24] and in [25].

Nielsen et al. [26] presented a method for comparing the energy performance of glazings or windows for heating dominated buildings. The net energy gain is calculated for the heating season and is equal to the solar gains minus the heat losses through the glazing. Following this method, diagrams presenting the net energy gain for different combinations of SHGC and U-values are generated for a specific orientation. These diagrams are useful since they allow to quickly visualize what is the optimum window for a given orientation. Heat gains can be reduced by employing a shading coefficient to represent overhangs or obstructions, but only a fixed value for the year can be simulated. This simple method can be used either with glazings or whole windows, but cannot evaluate the impact of shading devices.

For achieving low energy buildings with satisfactory indoor climate, the designers have to be aware as early as possible of the consequences of critical design decisions [27]. Tools with simplified input are needed for supporting decisions in the early design stages of a building [28].

The most accurate way of analyzing the performance of windows and shading devices is with detailed dynamic energy building simulations for a specific building and climate [14]. Lee et al. [4], among others, have identified different optimal window properties in different climates and different optimal window properties for different orientations in the same location. These results emphasize the need of evaluating different window properties when designing energy efficient buildings. However, analyzing multiple coupled variables such window size and type, shading type, properties and control, for all four orientations of a building can yield to a very large solution space.

One way to reduce the solution space of whole building simulations is to first use single space models to identify optimum shade designs and then analyze the identified optimums with whole building simulations, an approach followed by Orsi [29].

As an alternative, the methodology described in this paper can be used first to identify optimum glazing and shading combinations as a function of orientation before carrying whole building simulations. Once implemented, the proposed methodology can be readily used at the design stage for a new project and requires significantly less effort that developing new single space building models.

1.3. Objectives and overview

After reviewing the existing tools, it can be seen that there is a need to develop a simple tool to be used at the preliminary design stage allowing the comparison of the net energy balance of various fenestration systems. The influence of the shades on the SHGC and U-value of the fenestration system must be accounted for in the energy balance. In addition, the control of shades should be customizable.

The goal of this paper is to present a methodology for selecting optimum fenestration systems. It has the capability of calculating the net energy gain of windows with one interior and/or one exterior shade(s), which covers most important cases. This methodology can be used independently or as an early stage design tool for identifying fenestration systems with the best performance before running whole building simulations.

The section 2 below presents the methodology for comparing the net energy balance of unshaded glazings, glazings with an exterior shade, glazings with an interior shade and glazings with both interior and exterior shades. It is based from [26], where some modifications were introduced to increase its accuracy and where the capability of analyzing shades has been integrated. Applications and limitations of this methodology are detailed in section 3 along with some recommendations. Results are then presented in section 4, where diagrams for glazings with an interior roller shade, an exterior roller shutter and a combination of both are presented for the four cardinal orientations for the city of Montreal. Finally, section 5 presents a comparison of experimental and simulated U-values for four types of shading devices.

The methodology presented in this paper can be used for comparing either glazings or complete windows. For clarity, equations are presented for glazings only throughout this paper. Appendix B describes how to adapt the calculations for investigating complete windows.

2. Methodology for selecting fenestration systems

Canadian Weather for Energy Calculations (CWEC) files were used for this study. Any hourly weather data freely available on the US DOE [30] website can be downloaded and serve as input. The inputs required are the time and day of the year, outdoor temperature, global horizontal radiation, direct normal radiation and diffuse horizontal radiation.

2.1. Unshaded glazings

The diffuse and beam solar radiation incident on a window are calculated from the direct normal and diffuse horizontal radiation. Details are presented in Appendix A.

2.1.1. Calculating net energy gain

The net energy gain (or loss) through a glazing or a window is calculated as

$$Q = SHGC \cdot I - U \cdot D \tag{1}$$

where I and D are given as

$$I = \eta F_s \sum_t \left(I_b \, g_j(\theta_i) \Delta t + I_{ds,ho} f_j \Delta t \right) \quad \text{for } T_o < T_b \tag{2}$$

$$D = \sum_t (T_i - T_o) \Delta t \quad \text{for } T_o < T_b \tag{3}$$

The angular profile g_j is used to approximate the dependency of the SHGC to the incidence angle. f_j represents the ratio of the SHGC for diffuse radiation to the SHGC at normal incidence. It is calculated with [31]

$$f_j = 2 \int_0^{\pi/2} g_j(\theta) sin(\theta) cos(\theta) \tag{4}$$

f_j and g_j are provided in Table 6 in Appendix A as a function of the number of panes j. Although the angular profiles have been determined for clear glass, they have shown a mean average error of 1% and a maximum error of 5% when used with a variety of coated glass [32]. A more detailed polynomial method presented in the work cited above can be used if a higher accuracy is required.

T_i from equation 3 is the average interior temperature during the heating season.Equations 2 and 3 are computed only when the outdoor temperature T_o is below the balance temperature T_b. The balance temperature is usually defined as the value of the outdoor temperature when the internal and solar gains are equal to the building heat losses [33, Chapter 19]. However, for the purpose of this study, the solar gains are actually useful for eliminating heating needs and thus their contributions should be accounted for. Therefore, the balance temperature used here should consider internal gains only and can be calculated from

$$q = UA(T_i - T_b) \tag{5}$$

For residential buildings, the internal gains can be estimated with [33, Chapter 17]

$$q = 136 + 2.2A_{floor} + 22N_{oc} \tag{6}$$

The balance temperature could be 1 °C lower than T_i for old houses with little insulation while it could be 5 °C lower than T_i for highly insulated houses like passive houses. For non-residential buildings, internal gains should be determined accordingly to the expected building occupancy and equipment. One may refer to ASHRAE [33, Chapter 18] for more details.

To avoid considering useful heat gains in the hot season when no heating is used, equations 2 and 3 should be computed only during the heating season and transitional periods.

F_s in equation 2 represents a shading factor. This factor represents shading from distant objects, window reveals and fixed exterior shadings. It is possible to use a fixed value throughout the year, or, as an alternative, monthly shading factors for various types of external shading elements can be obtained with ParaSol [19]. [1]

[1] In this software, the f(g) output variable represents the shading factor of the obstruction under consideration. The graphical output can be easily exported to a text file and then imported for use with this methodology.

The value of the utilization factor η in equation 2 should be very close to 1. This method is intended for buildings in heating dominated climates aiming at a high solar utilization, in which case the solar gains as calculated with equation 2 are practically always useful. Please refer to section 3 for further details about the applications and limitations of this methodology.

2.1.2. Generating net energy gain diagram

Equations 1, 2 and 3 are then used to generate lines of constant energy gains or losses. First, an array of energy gains (or losses) is defined, in kWh/m^2 of window area. For instance, in Figure 1, Q is an array between -300 and 500 kWh/m^2 with an increment of 50 kWh/m^2.

Secondly, an array of possible SHGC must also be defined. Then, the user must determine the number of panes he is primarily interested in, for comparison purposes. Using the corresponding corrected incident solar radiation I, from equation 2, an array of U-values required to achieve a specific energy performance is calculated from isolating U in equation 1. Plotting the SHGC array as a function of these U-values generates a diagram with lines of constant net energy gains (or losses).

After entering the U-value and SHGC of a few glazings of interest, their performance can then be easily compared for a given orientation. Figure 1 shows the performance of six different glazings on a south façade in Montreal.

The corrected incident radiation for single, double and triple glazings is presented in Table 1 for Montreal for the conditions described in Figure 1. The constant net energy gain lines in this figure have been calculated for a double glazing. Although both double and triple window products are depicted on the figure, it can be seen from Table 1 that the difference between the corrected incident radiation for single and double glazing is 2.2% and for double and triple glazing is less than 1%. Therefore, it is possible to compare glazings with a different number of panes on the same graphic with a reasonable accuracy.

Table 1: Corrected incident solar radiation for a single, double and triple glazing, in kWh/m^2

I_1	I_2	I_3
621	607	602

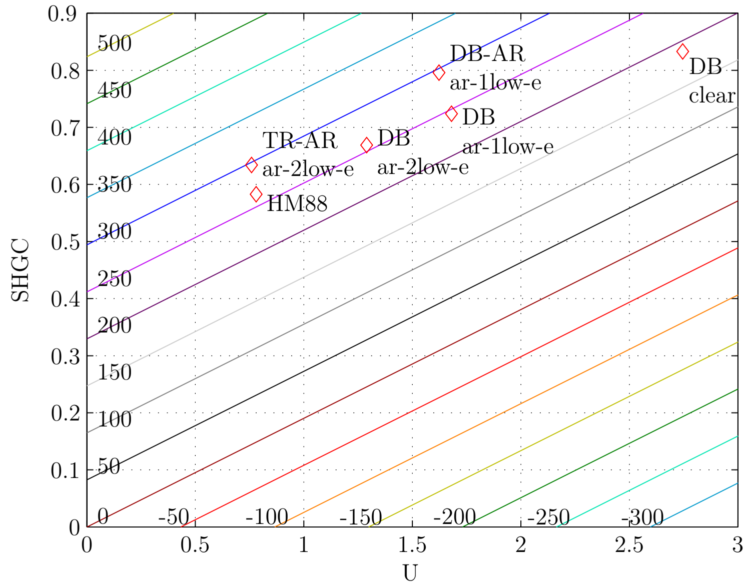


Figure 1: Diagram of net energy gains (in kWh/m^2) for glazings on a south orientation in Montreal with F_s=0.9, η=1 during the heating period ranging from 15/09 to 15/05, for T_b=20°C. DB=Double; TR=Triple; AR=antireflective coating; ar=argon; low-e=low emissivity; HM88=DB glazing with suspended low-e plastic film.

2.2. Glazings with shading devices

The shade is assumed to cover the glazing only. Single, double and triple glazings can be analyzed with the presence of an exterior or interior shade, or a combination of both.

The required inputs for glazings and shades are summarized in Table 2. Ideally, the solar transmittance and absorptance of window panes should be known. However, as an alternative, this paper presents tables to estimate these values for single, double and triple glazing where only the composition of the gas infill is required. In rare cases, if the emissivity of the outermost or innermost pane is different than 0.84, then it should be specified.

Shades can be controlled based on a hourly schedule, a solar radiation set point or on more detailed conditions determined by the user. It is also possible to use another program to perform a more complete thermal analysis to determine an annual operation schedule and import it into this methodology.

U-values of fenestration systems are calculated based on interior and ex-

Table 2: Inputs parameters (*optional, for the analysis of windows only)

Glazing
U-value
SHGC
Solar transmittance and absorptances OR Gas infill and nb of panes
Emissivity of outermost and innermost panes, if $\neq 0.84$
Height and width of glazing (or window*)
*Window U-value
*Window area
Shade
Emissivity of both sides (typically ≈ 0.9)
Thermal resistance OR thermal conductivity and thickness
Solar absorptance
Solar transmittance
Solar reflectance of the window facing side
Cavity width between the shade and the window
Openness factor
Top/bottom/left/right opening area between the shade and glass

terior temperatures T_i^* and T_o^* as defined in NFRC 100-2004 [34] (T_o^*=-18°C and T_i^*=21°C) for North America or in ISO 15099 [35] (T_o^*=0°C and T_i^*=20°C) for Europe.

2.2.1. Glazings with exterior shade

First, the U-value of the window without the exterior heat transfer coefficient is calculated

$$U'_{\text{øh}_{ext}} = \frac{1}{1/U_g - 1/h_{ext}} \tag{7}$$

$$h_{ext} = h_{c,ext} + h_{r,ext} \tag{8}$$

with $h_{c,ext} = 26\,W/(m^2K)$ for north American windows [34] or $20\,W/(m^2K)$ for European windows [35]. $h_{r,ext}$ is calculated with

$$h_{r,ext} = \frac{\epsilon_{w,o}\sigma(T_{w,o}^4 - T_o^{*4})}{(T_{w,o} - T_o^*)} \tag{9}$$

$T_{w,o}$ is determined from an energy balance at the environmental conditions, as defined in NFRC 100-2004 or ISO 15099. $T_{w,o}$ and $h_{r,ext}$ are calculated iteratively until convergence.

Secondly, the resistance of the air cavity between the shade and the window must be evaluated. The radiative coefficient exchange between the outer pane of the window and the shade is calculated with

$$h_r = \frac{\sigma(T_{w,o}^2 + T_{s,i}^2)(T_{w,o} + T_{s,i})}{1/\epsilon_{w,o} + 1/\epsilon_{s,i} - 1} \tag{10}$$

The convective coefficient in the air cavity is calculated following the procedure outlined in ISO 15099 [35] for thermally driven ventilation. The convective coefficient in a ventilated gap is given by

$$h_{c,v} = 2h_{c,nv} + 4v \tag{11}$$

A pressure-balance equation is used to determine the mean air velocity in the cavity and other variables of interest. The heat balance equations are solved iteratively until convergence is reached. More details about the procedure for calculating $h_{c,nv}$ and v can be found in [35] or in the documentation of EnergyPlus where the equations are all clearly stated [20]. The total thermal conductance of the air cavity is given by

$$h_{ExtS} = h_{c,v} + h_r \tag{12}$$

The exterior radiative coefficient $h_{r,ext}$ must be recalculated based on the temperature of the shade. The exterior convective coefficient $h_{c,ext}$ remains unchanged. Because the calculation of the radiative coefficient depends on the temperature of the surfaces, energy balance equations must be solved iteratively until convergence is reached. The U-value of the whole fenestration system is finally calculated as

$$U_{ExtS} = \frac{1}{1/U'_{\o \mathrm{h}_{ext}} + 1/h_{ExtS} + R_{ExtS} + 1/h_{ext}} \tag{13}$$

Figure 2 summarizes the process for calculating the equivalent U-value. The net energy gain must be calculated hourly taking into account if the

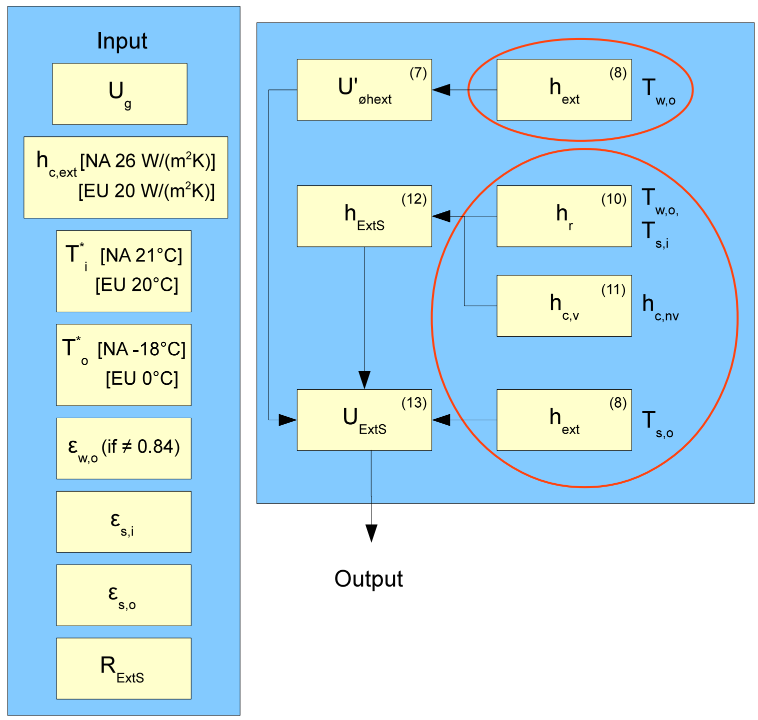


Figure 2: Flow chart for calculating the equivalent U-value of a fenestration system with an exterior shade. The ovals indicate that calculations are made iteratively until convergence is reached.

shade is present or not:

$$
\begin{aligned}
&\text{if shade is absent} \\
&\qquad Q'_t = SHGC_g I_j - U_g(T_i - T_o) \\
&\qquad U'_{\mathrm{t}} = U_g \\
&\text{else} \\
&\qquad Q'_t = SHGC_{ExtS} I_j - U_{ExtS}(T_i - T_o) \\
&\qquad U'_{\mathrm{t}} = U_{ExtS}
\end{aligned}
\tag{14}
$$

The effective U-value of the fenestration system is simply the average of U'_{t} and the net energy gain is the hourly sum of Q'_t

$$U_{\text{eff}} = \text{avg}(U'_{\mathrm{t}}) \tag{15}$$

$$Q = \sum_t Q'_t \tag{16}$$

The effective solar heat gain is calculated with

$$SHGC_{\text{eff}} = \frac{(Q + U_{\text{eff}} D)}{I} \tag{17}$$

where I and D are calculated from equations 2 and 3. Situating $(U_{\text{eff}}, SHGC_{\text{eff}})$ on a net energy gain diagram will indicate the net energy balance of the investigated fenestration system. Note that $SHGC_{\text{eff}}$ is used only to situate the net energy balance Q on the graph. While it gives an indication about how the shade and its control are reducing the equivalent solar heat gain of a fenestration system, it has no explicit physical meaning. Under some circumstances, its value can be above the SHGC at normal incidence of a bare window.

The presence of a shade affects not only the U-value of a fenestration system but also its SHGC. The SHGC of a fenestration system depends on the solar transmittance and absorptance of the different layers [35]:

$$SHGC_{1g} = \tau + \alpha_1 \frac{U}{h_{ext}} \tag{18a}$$

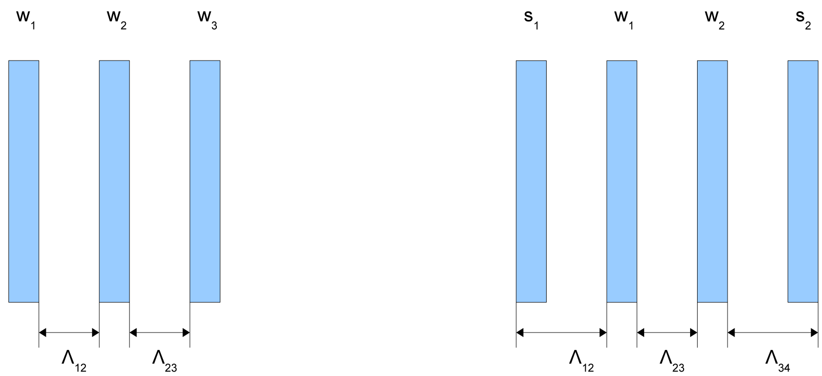
$$SHGC_{2g} = \tau + \alpha_1 \frac{U}{h_{ext}} + \alpha_2 \frac{(h_{int} - U)}{h_{int}} \tag{18b}$$

$$SHGC_{3g} = \tau + \alpha_1 \frac{U}{h_{ext}} + \alpha_2 U \left(\frac{1}{h_{ext}} + \frac{1}{\Lambda_{12}} \right) + \alpha_3 \frac{(h_{int} - U)}{h_{int}} \tag{18c}$$

$$SHGC_{4g} = \tau + \alpha_1 \frac{U}{h_{ext}} + \alpha_2 U \left(\frac{1}{h_{ext}} + \frac{1}{\Lambda_{12}} \right) + \alpha_3 U \left(\frac{1}{h_{ext}} + \frac{1}{\Lambda_{12}} + \frac{1}{\Lambda_{23}} \right) + \alpha_4 \frac{(h_{int} - U)}{h_{int}} \tag{18d}$$

where Λ_{ij} represents the thermal conductance of the cavity between elements i and j, as depicted in Figure 3. The thermal resistance of the glass is always very small and therefore neglected, but the thermal resistance of the shade is accounted for since it could be significant in some cases. Layers are numbered with #1 being the outermost layer.

It is assumed that the dependency of the SHGC of the shading material with the incidence angle is identical as the glazing under investigation. This assumption seems reasonable especially with some shading materials like roller shades and insect screens where the analysis of their beam total transmittance was shown to exhibit a similar trend than glass [36, 37].



(a) (b)

Figure 3: Illustration of the thermal conductances Λ_{ij} for different configurations — (a) Triple glazing (b) Double glazing with exterior and interior shades

The total transmittance of a glazing with an outer shade is calculated with

$$\tau_{ExtS} = \frac{\tau_s \tau_g}{1 - \rho'_s \rho_g} \tag{19}$$

Glazings, either single, double or triple, are considered as a single element with their solar transmittance estimated with Tables 7 - 9 if actual data is not available. The prime in equation 19 refers to the spectral reflectance measured in the opposite direction of the incident solar radiation. The typical solar reflectance of uncoated glass is 0.08.

As seen in equations 18, calculating the SHGC of a window with a shade requires the knowledge of the solar transmittance and absorptance of the window panes. Ideally, they should be specified as input. As an alternative, a simple method estimating the solar transmittance and absorptances of a glazing from its U-value, SHGC and gas infill has been developed and is presented in Tables 7, 8 and 9 in Appendix C. The absolute average and maximum associated errors and shown in Table 10.

The total SHGC of a fenestration system that consists of an outer shade and a single, double or triple glazing is calculated with

$$SHGC_{1gExtS} = \tau_{ExtS} + \alpha_s \frac{U_{ExtS}}{h_{ext}} + \tau_{ExtS}\alpha_g \frac{(h_{int} - U_{ExtS})}{h_{int}} \tag{20a}$$

$$\begin{aligned} SHGC_{2gExtS} =& \tau_{ExtS} + \alpha_s \frac{U_{ExtS}}{h_{ext}} + \tau_{ExtS}\alpha_{g1} U_{ExtS} \left(\frac{1}{h_{ext}} + \frac{1}{h_{ExtS} + 1/R_{ExtS}} \right) \\ &+ \tau_{ExtS}\alpha_{g2} \frac{(h_{int} - U_{ExtS})}{h_{int}} \end{aligned} \tag{20b}$$

$$\begin{aligned} SHGC_{3gExtS} =& \tau_{ExtS} + U_{ExtS} \frac{\alpha_s + \tau_{ExtS}\alpha_{g1} + \tau_{ExtS}\alpha_{g2} + \tau_{ExtS}\alpha_{g3}}{h_{ext}} \\ &+ U_{ExtS} \frac{\tau_{ExtS}\alpha_{g1} + \tau_{ExtS}\alpha_{g2} + \tau_{ExtS}\alpha_{g3}}{(1/h_{ExtS} + R_{ExtS})^{-1}} \\ &+ U_{ExtS} \frac{\tau_{ExtS}\alpha_{g2} + \tau_{ExtS}\alpha_{g3}}{\Lambda_{23}} + U_{ExtS} \frac{\tau_{ExtS}\alpha_{g3}}{\Lambda_{34}} \end{aligned} \tag{20c}$$

In the case of a triple glazing with an exterior shade, the insulating value of the glass cavities, Λ_{23} and Λ_{34}, should be known to determine the SHGC of the fenestration system. This would require the knowledge of the emissivity of panes #2, #3 #4 and #5 as well as the cavity thicknesses and gas infill. If this information is known, Λ_{23} and Λ_{34} can be calculated using equation 3 from ISO 10292 [38]. Alternatively, they can be approximated with

$$\Lambda_{23} = \Lambda_{34} = \frac{1}{\left(\frac{1}{U_g} - \frac{1}{h_{ext}} - \frac{1}{h_{int}}\right)/2} \tag{21}$$

where h_{ext} is calculated using equation 8 and h_{int} can be calculated with equation 23 from section 2.2.2.

2.2.2. Glazings with interior shade

As a first step, the U-value of the window without the interior heat transfer coefficient is estimated from

$$U'_{\text{øh}_{int}} = \frac{1}{1/U_g - 1/h_{int}} \tag{22}$$

where

$$h_{int} = h_{c,int} + h_{r,int} \tag{23}$$

The interior radiative coefficient $h_{r,int}$ is calculated with [35]

$$h_{r,int} = \frac{\epsilon_{w,i}\sigma(T_{w,i}^4 - T_i^{*4})}{(T_{w,i} - T_i^*)} \tag{24}$$

The interior convective coefficient is calculated with

$$h_{c,int} = \frac{Nu\, k}{H_g} \tag{25}$$

where Nu is calculated as described in ISO 15099 [35, section 8.2.1.1].

Then, the resistance of the air cavity between the shade and the window must be evaluated. The radiative coefficient exchange between the inner pane of the window and the shade is calculated as in equation 10 where $T_{w,o}$ is replaced by $T_{w,i}$, $T_{s,i}$ is replaced with $T_{s,o}$, $\epsilon_{w,o}$ is replaced by $\epsilon_{w,i}$ and $\epsilon_{s,i}$ is replaced by $\epsilon_{s,o}$. The convective coefficient of the window/shade cavity is calculated based on equation 11. The total resistance of the air space between the interior shade and the window is given by

$$h_{IntS} = h_{c,v} + h_r \tag{26}$$

The interior radiative and convective coefficient $h_{r,int}$ and $h_{c,int}$ must be recalculated based on the shade temperature using equations 24 and 25. Again, energy balance equations must be solved iteratively until convergence is reached. The U-value of the fenestration system is then calculated as

$$U_{IntS} = \frac{1}{1/U'_{\text{øh}_{int}} + 1/h_{IntS} + R_{IntS} + 1/h_{int}} \tag{27}$$

The calculation procedure is summarized in Figure 4.

Finally, the effective U-value and SHGC can be calculated using equations 16 and 17 to determine graphically the net energy balance. Equations 39 and 40 must be used if windows are analyzed. If the shade is to be closed during sunny hours, Tables 7-9 must be used to estimate the appropriate solar transmittance and absorptance of the window (if unknown) in order to evaluate the SHGC with the shade on. The total transmittance of a glazing with an inner shade is calculated with

$$\tau_{IntS} = \frac{\tau_g \tau_s}{1 - \rho'_g \rho_s} \tag{28}$$

where ρ'_g is the reflectance of the innermost pane.

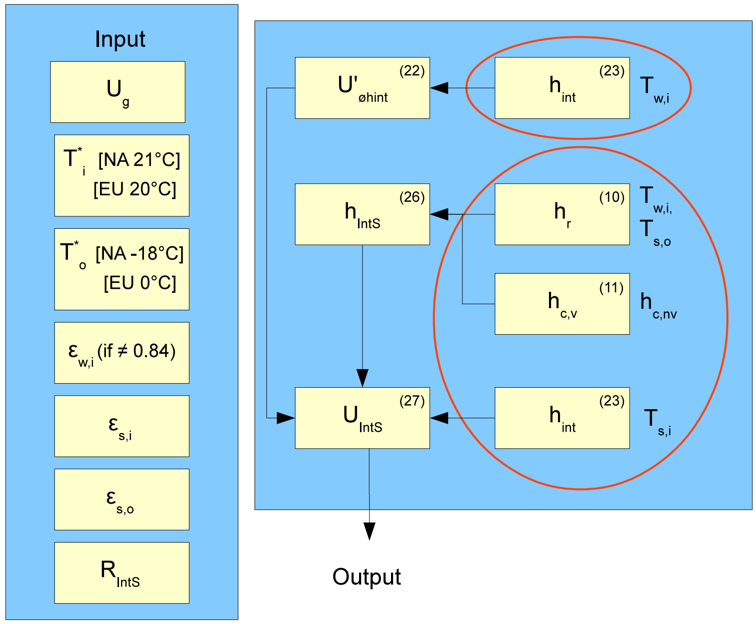


Figure 4: Flow chart for calculating the equivalent U-value of a fenestration system with an interior shade.

348 The total SHGC of a fenestration system that consists of a single, double
349 or triple glazing with an inner shade is determined with:

$$SHGC_{1gIntS} = \tau_{IntS} + \alpha_g \frac{U_{IntS}}{h_{ext}} + \tau_g \alpha_s \frac{(h_{int} - U_{IntS})}{h_{int}} \tag{29a}$$

$$\begin{aligned} SHGC_{2gIntS} =& \tau_{IntS} + U_{IntS} \frac{\alpha_{g1} + \alpha_{g2} + \tau_g \alpha_s}{h_{ext}} \\ &+ U_{IntS}(\alpha_{g2} + \tau_g \alpha_s) \left(\frac{1}{U_{IntS}} - \frac{1}{h_{ext}} - \frac{1}{h_{int}} - \frac{1}{h_{IntS}} - R_{IntS} \right) \\ &+ U_{IntS} \frac{\tau_g \alpha_s}{(1/h_{IntS} + R_{IntS})^{-1}} \end{aligned} \tag{29b}$$

$$\begin{aligned} SHGC_{3gIntS} =& \tau_{IntS} + U_{IntS} \frac{\alpha_{g1} + \alpha_{g2} + \alpha_{g3} + \tau_g \alpha_s}{h_{ext}} \\ &+ U_{IntS} \frac{\alpha_{g2} + \alpha_{g3} + \tau_g \alpha_s}{\Lambda_{12}} + U_{IntS} \frac{\alpha_{g3} + \tau_g \alpha_s}{\Lambda_{23}} \\ &+ U_{IntS} \frac{\tau_g \alpha_s}{(1/h_{IntS} + R_{IntS})^{-1}} \end{aligned} \tag{29c}$$

In the case of a triple glazing with an interior shade, Λ_{12} and Λ_{23} should be known. They can be calculated individually with ISO 10292 [38, equation 3] if the emittance of panes is known or approximated with equation 21, where h_{ext} can be calculated with equation 8 from section 2.2.1.

2.2.3. Glazings with interior and exterior shades

Essentially, the same procedure as described in sections 2.2.1 and 2.2.2 is followed. The U-value of a glazing without the interior and exterior heat transfer coefficients is estimated from

$$U'_{\text{øh}_{ext}\&\text{h}_{int}} = \frac{1}{1/U_g - 1/h_{ext} - 1/h_{int}} \tag{30}$$

where h_{ext} and h_{int} are calculated with equations 8 and 23. The exterior radiative coefficient and the interior radiative and convective coefficients are recalculated to account for the presence of shades with equations 9, 24 and 25.

The convection and radiation exchanges in the window/shade cavities must be calculated with equations 10 and 11. Finally, knowing the thermal resistance of both shades, the U-value of the fenestration system is calculated with

$$U_{IntExtS} = \frac{1}{1/U'_{\text{øh}_{ext}\&\text{h}_{int}} + 1/h_{IntS} + 1/h_{ExtS} + R_{IntS} + R_{ExtS} + 1/h_{int} + 1/h_{ext}} \tag{31}$$

The U-values of the fenestration system with only the exterior or interior shade drawn must also be calculated with equations 27 and 13 if they are to be controlled independently. Figure 5 summarizes the calculation procedure for a fenestration system with interior and exterior shades.

The total solar energy transmittance of the fenestration system is calculated with

$$\tau_{IntExtS} = \frac{\tau_{s1}\tau_g\tau_{s2}}{(1-\rho'_{s1}\rho_g)(1-\rho'_g\rho_{s2}) - \tau_g^2\rho'_{s1}\rho_{s2}} \tag{32}$$

where ρ_g and ρ'_g are the reflectance of the outermost and innermost pane. The effective U-value and SHGC are calculated using equations 16 and 17. Tables 7-9 are used to estimate the solar absorptances and transmittance of the glazing (if unknown) if shades are to be closed during sunny hours.

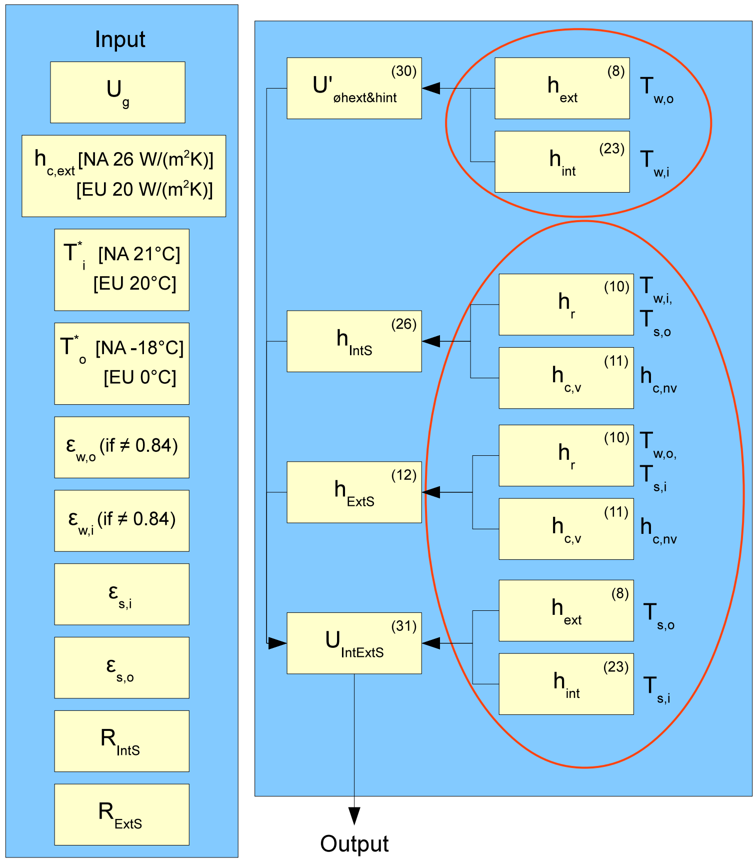


Figure 5: Flow chart for calculating the equivalent U-value of a fenestration system with interior and exterior shades.

The total SHGC of a fenestration system that consists of a single, double or triple glazing with an inner and outer shade is calculated with

$$SHGC_{1gIntExtS} = \tau_{IntExtS} + \alpha_{s1}\frac{U_{IntExtS}}{h_{ext}} + \tau_{s1}\alpha_g\left(\frac{1}{h_{ext}} + \frac{1}{h_{ExtS}} + R_{ExtS}\right) + \tau_{s1}\tau_g\alpha_{s2}\frac{(h_{int} - U_{IntExtS})}{h_{int}} \quad (33a)$$

$$
\begin{aligned}
SHGC_{2gIntExtS} = {} & \tau_{IntExtS} + U_{IntExtS}\frac{\alpha_{s1} + \tau_{s1}\alpha_{g1} + \tau_{s1}\alpha_{g2} + \tau_{s1}\tau_g\alpha_{s2}}{h_{ext}} \\
& + U_{IntExtS}\frac{\tau_{s1}\alpha_{g1} + \tau_{s1}\alpha_{g2} + \tau_{s1}\tau_g\alpha_{s2}}{(1/h_{ExtS} + R_{ExtS})^{-1}} \\
& + U_{IntExtS}(\tau_{s1}\alpha_{g2} + \tau_{s1}\tau_g\alpha_{s2}) \\
& \cdot \left(\frac{1}{U_{IntExS}} - \frac{1}{h_{ext}} - \frac{1}{h_{int}} - \frac{1}{h_{ExtS}} - R_{ExtS} - \frac{1}{h_{IntS}} - R_{IntS}\right) \\
& + U_{IntExS}\frac{\tau_{s1}\tau_g\alpha_{s2}}{(1/h_{IntS} + R_{IntS})^{-1}} \qquad (33b)
\end{aligned}
$$

$$
\begin{aligned}
SHGC_{3gIntExtS} = {} & \tau_{IntExtS} + U_{IntExtS}\frac{\alpha_{s1} + \tau_{s1}\alpha_{g1} + \tau_{s1}\alpha_{g2} + \tau_{s1}\alpha_{g3} + \tau_{s1}\tau_g\alpha_{s2}}{h_{ext}} \\
& + U_{IntExtS}\frac{\tau_{s1}\alpha_{g1} + \tau_{s1}\alpha_{g2} + \tau_{s1}\alpha_{g3} + \tau_{s1}\tau_g\alpha_{s2}}{(1/h_{ExtS} + R_{ExtS})^{-1}} \\
& + U_{IntExtS}\frac{\tau_{s1}\alpha_{g2} + \tau_{s1}\alpha_{g3} + \tau_{s1}\tau_g\alpha_{s2}}{\Lambda_{23}} \\
& + U_{IntExtS}\frac{\tau_{s1}\alpha_{g3} + \tau_{s1}\tau_g\alpha_{s2}}{\Lambda_{34}} + U_{IntExtS}\frac{\tau_{s1}\tau_g\alpha_{s2}}{(1/h_{IntS} + R_{IntS})^{-1}} \\
& \qquad (33c)
\end{aligned}
$$

If shades are to be controlled independently, equations 20 and 29 should also be used to calculate the appropriate SHGC with only one shade being used.

In the case of a triple glazing, Λ_{23} and Λ_{34}, can be calculated from ISO 10292 [38, equation 3] or estimated with equation 21.

3. Applications, limitations and recommendations

3.1. Applications

This methodology is intended to be used for the design of buildings aiming at a high solar utilization. It is suitable for heating dominated buildings like solar houses and solariums/greenhouses in cold climates where maximizing the net energy balance of windows is usually an important concern. In addition, this methodology may be useful to other kinds of buildings in heating dominated climates where a *solar optimized fenestration systems* approach has been adopted.

The *solar optimized fenestration systems* concept designate a design approach where the role of windows is to maximize the net energy balance and the role of shading devices is to control overheating and glare issues as well as improving the energy balance.

As seen from the literature review, this idea is not new. Hee et al. [7], after carrying an extensive review on static and dynamic windows, have suggested that heating dominated countries shall adopt high SHGC windows to reduce heating loads and use shading devices in summer to prevent overheating.

In heating dominated climates, the use of efficient shading devices for solar and glare control allows the adoption of high SHGC windows, which in turn yields the maximum benefits from passive solar design. With good protections, high SHGC glazings can be selected for either view and/or daylighting sections, for all orientations. Since the SHGC is closely related to the visible transmittance value [12], a high SHGC window will generally improve daylighting as an added benefit.

Following the *solar optimized fenestration systems* design concept in heating dominated climates allows to decouple the complex issues related to glazing and shading design like solar gains/overheating and daylighting/glare. The selection of a window optimized for maximizing the energy balance and shading systems optimized for solar and glare control greatly simplifies the problem and reduces the number of possibilities to investigate. Since glazing alone cannot solve excessive heat gains and discomfort [12], shadings must be incorporated. If well designed for solar and glare control, the glazing is now free from these constraints and can then be optimized for high solar gains and low thermal losses only, simplifying the design process and enhancing passive solar design efficiency.

Once implemented into a programming software, this methodology can be readily used during the design stage of a new building or when considering windows replacement of an existing building. It is a flexible method that can be used at any location within heating dominated countries as long as appropriate weather files are available. Diagrams for all façades orientations can be quickly generated, allowing the comparison of the net energy balance of different fenestration systems where the effect of the presence of an interior and/or exterior planar shade(s) can be analyzed.

This methodology can also be used to visualize the impact of shades on the U-value of fenestration systems, which could be useful when assessing thermal comfort and the need for perimeter heating. Tzempelikos et al. [2] have found that windows with $U<1.5$ W/(m^{2}K) could eliminate the need for perimeter heating.

Bülow-Hübe [39] has estimated possible annual energy savings up to

110 kWh per window for upgrading the windows of a house built in the 60's, which could lower the heating load by 6%. For a house built in 2000, energy savings of up to 50 kWh per window could be achieved, which would reduce the heating load by 9%. Since glazing type was identical for all orientations in this study and shading devices were not considered, higher savings could be obtained when using this methodology for selecting optimum fenestration systems for different orientations.

This methodology can be used for comparing either glazings or complete windows. Appendix B describes how to adapt the calculations for investigating complete windows.

3.2. Limitations

As this methodology is based on steady state calculations, it is not meant to provide an accurate estimation of the yearly total energy gained or loss through a fenestration but rather to assist the design process by comparing the performance of different products on a relative basis.

A comparison of dynamic computer simulations and a simplified method based on net energy gains carried out by Bülow-Hübe [39, Section 5.1.7] revealed discrepancies of only about 10% when comparing the savings due to a lower U-value window. However, it also points out that solar gains might be as much as 60% larger when no shading factor is used, which stresses out the importance of evaluating properly shadings from distant objects, window reveals and fixed shading devices when present.

This methodology can only evaluate the heat transfer of planar shading elements parallel to the glazing. The calculation of heat transfer due to fixed shadings such as overhangs, fins and louvres requires detailed computational fluid dynamic simulations and therefore cannot be evaluated with this methodology.

3.3. Recommendations

Since the operation of shades affects the energy performance, it is important that the simulation of shades is representative of their expected operation. Shades whose main purpose is to control solar gains that are used only during the warm period, such as manual exterior shutters, should not be considered when using this methodology. However, if motorized, they can also be used in the cold season to reduce night heat losses and should therefore be taken into consideration. As experience has shown that people are rather inconsistent when operating shades [40], motorized control is recommended.

During the design process, it is recommended to first use this methodology to help identifying the most appropriate glazing and shading combination for a given application and climate, so as to maximize the solar energy utilization from transparent components. Thereafter, it is suggested to follow passive solar principles to adequately position and size windows and select appropriate shading devices.

For instance, over-glazing should be avoided. Positioning windows mostly towards a southern exposure with overhangs and reducing window areas on east and west façades are well known passive solar techniques to reduce risks of overheating. The integration of interior thermal mass in direct gain rooms has shown to reduce temperature fluctuations appreciably and to slightly reduce heating loads [41, 42, Appendix B].

When the outdoor temperature is only a few degrees below the balance temperature, it is possible that not all solar gains are useful to reach the temperature set point. However, the extra heat can be stored, either in thermal mass or by elevating indoor air temperature, and be used later on. Therefore, by following good passive solar design practices, it is possible to utilize most of the solar gains considered useful in this method. This is why it is recommended to select a high utilization factor, typically around 0.98.

This method calculates energy gains and losses through fenestration systems for a constant interior temperature T_i. This temperature should be selected as the average interior temperature during the heating season. Interior temperature fluctuations in a house are typically small, usually less than 3 to 4 °C, while temperature fluctuations in a solarium or a greenhouse are likely to be more significant. Nevertheless, since this method is aiming to compare different design options on a relative basis, small fluctuations of the interior temperature will not significantly impact the results. If a greater accuracy is required, an average daily interior temperature profile could be easily defined for energy calculations.

4. Simulation results and discussion

4.1. Simulation results

Simulation results are presented for Montreal, with a solar shading factor of 0.9 and a solar gain utilization factor of 0.98. Figures 6 - 17 present the net energy gain per unit area for the four cardinal orientations of five different glazings with an exterior shade, an interior shade and the combination of both. For these simulations, shades have been open when the global horizontal solar radiation is above 50 W/m^2 and closed otherwise. Two common types of shadings have been simulated: an indoor roller shade and an exterior roller shutter. Their technical specifications are shown in Table 3.

Table 3: Technical properties of simulated shading devices

	Interior roller shade	Exterior roller shutter
Solar transmitance	0.26	0.01
Solar absorptance	0.34	0.19
Emissivity of outer side	0.9	0.9
Emissivity of inner side	0.9	0.9
Reflectance of outer side	0.4	-
Reflectance of inner side	-	0.8
Air cavity	0.03m	0.03m
Top opening	0.01m	0.001m
Bottom opening	0.01m	0.001m
Left opening	0.01m	0.001m
Right opening	0.01m	0.001m
Openness factor	0.14	0
Thermal resistance	0.01 Km^2/W	0.1 Km^2/W

4.2. Discussion

Some researchers predicted that «superwindows» with a U-value of 0.5 W/(m^2 K) and SHGC of 0.4 would be so efficient that even north facing windows could become net energy providers [40]. However, as it can be seen in Figure 8, the SHGC or the thermal resistance of a bare window must be significantly higher than that to generate a net energy gain in a southeastern Canadian climate like Montreal.

As expected, the presence of a shade has the biggest impact on the net energy balance of the least insulated glazing. Even when using both interior and exterior conventional shading devices, the net energy gain of a good triple glazing is only marginally improved, as illustrated on Figure 14-17. If one wishes to significantly improve the net energy gain of high performance triple glass, special insulating devices should be considered, such as interior cellular shades or exterior insulated shutters.

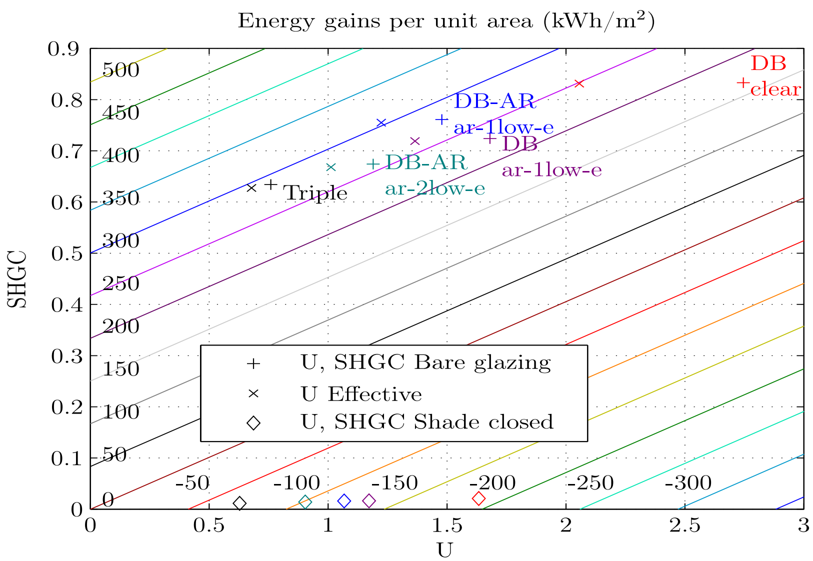


Figure 6: South, with exterior shade

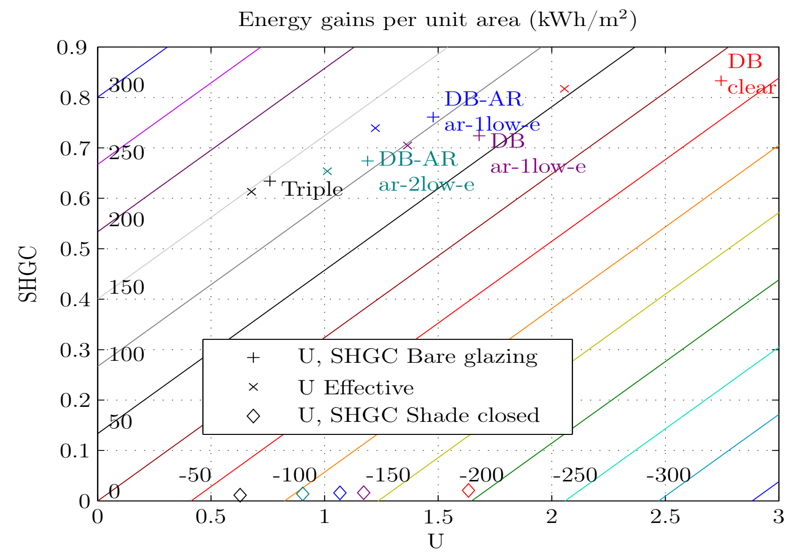


Figure 7: West, with exterior shade

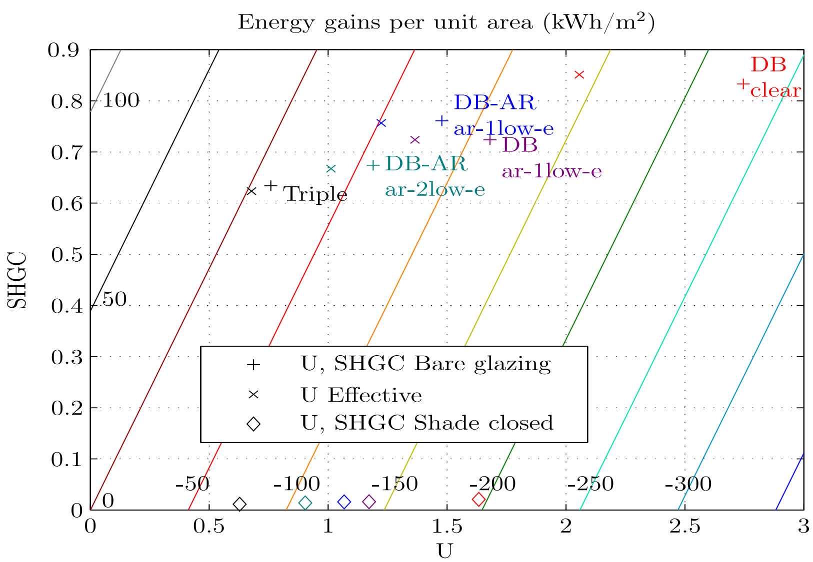


Figure 8: North, with exterior shade

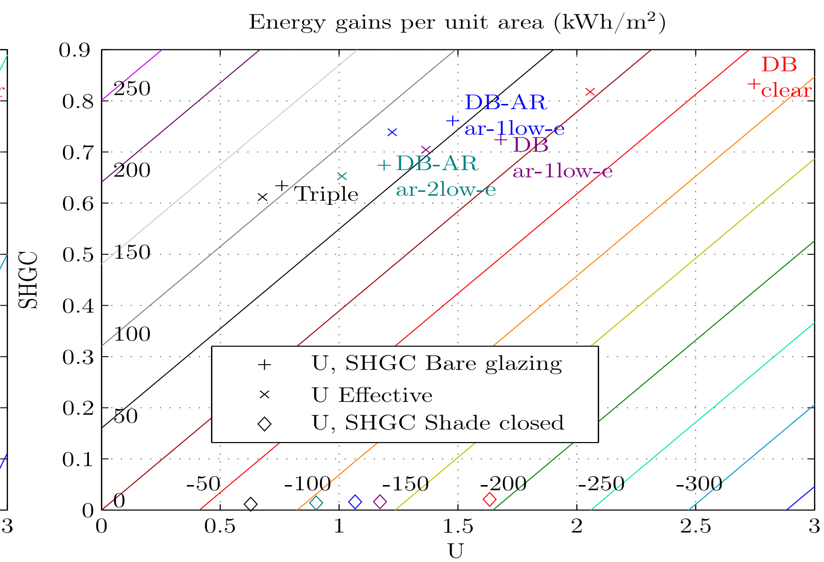


Figure 9: East, with exterior shade

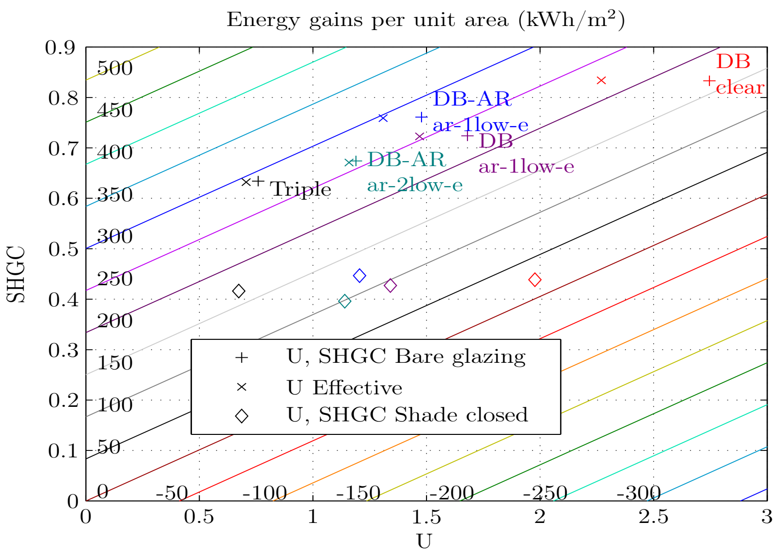


Figure 10: South, with interior shade

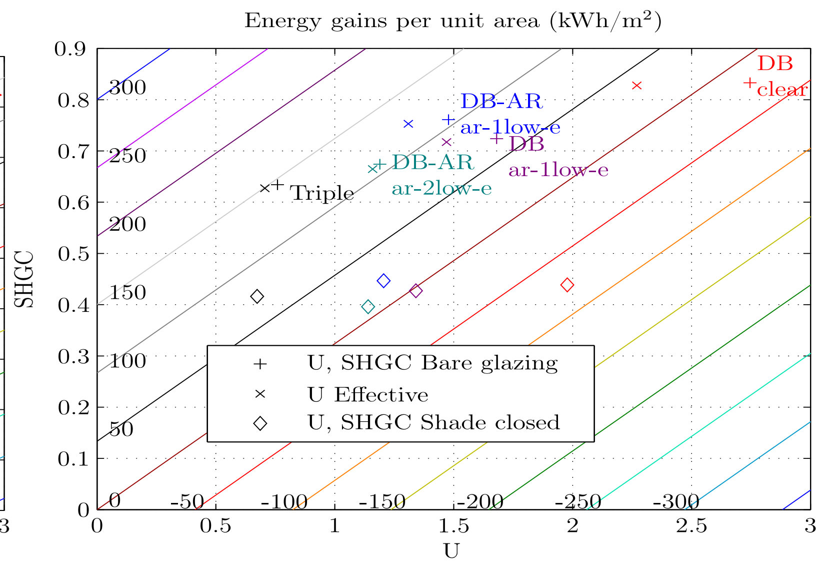


Figure 11: West, with interior shade

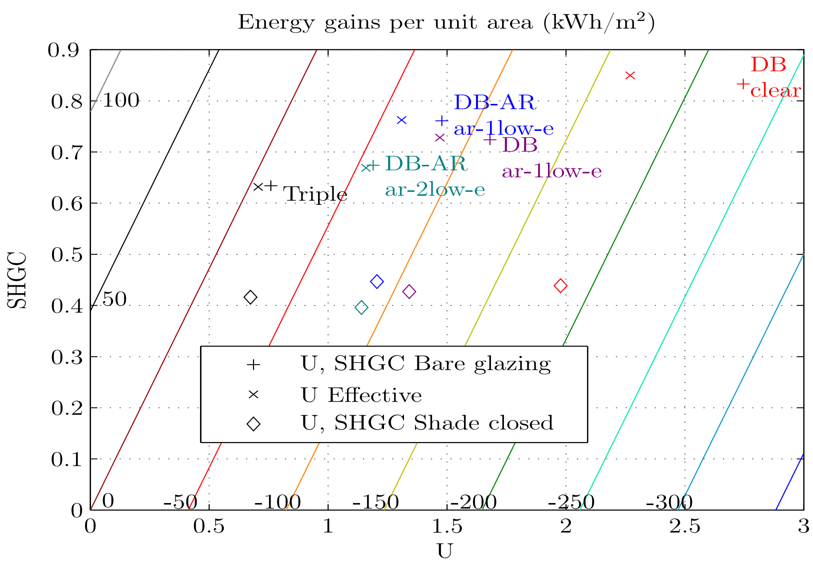


Figure 12: North, with interior shade

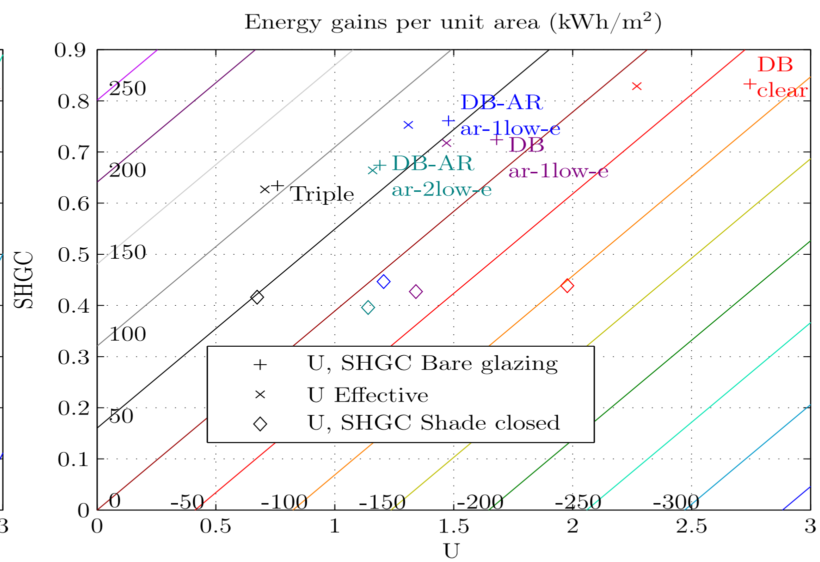


Figure 13: East, with interior shade

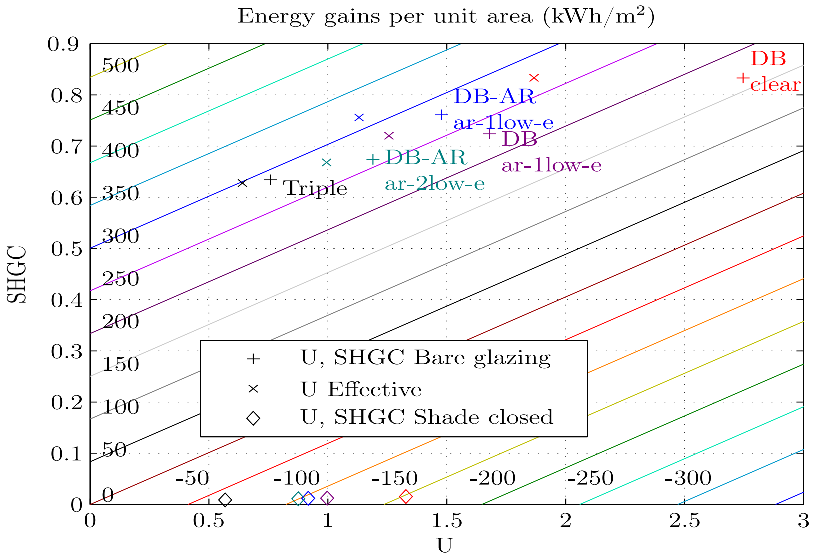


Figure 14: South, with exterior and interior shades

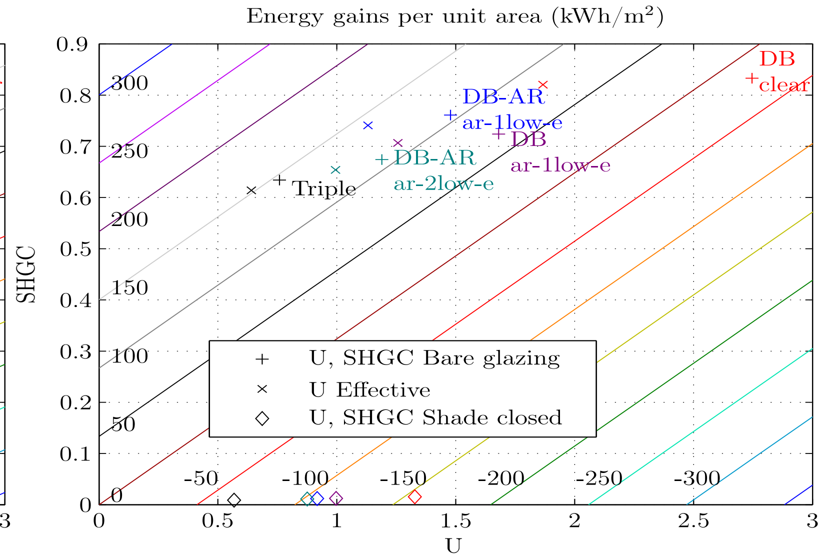


Figure 15: West, with exterior and interior shades

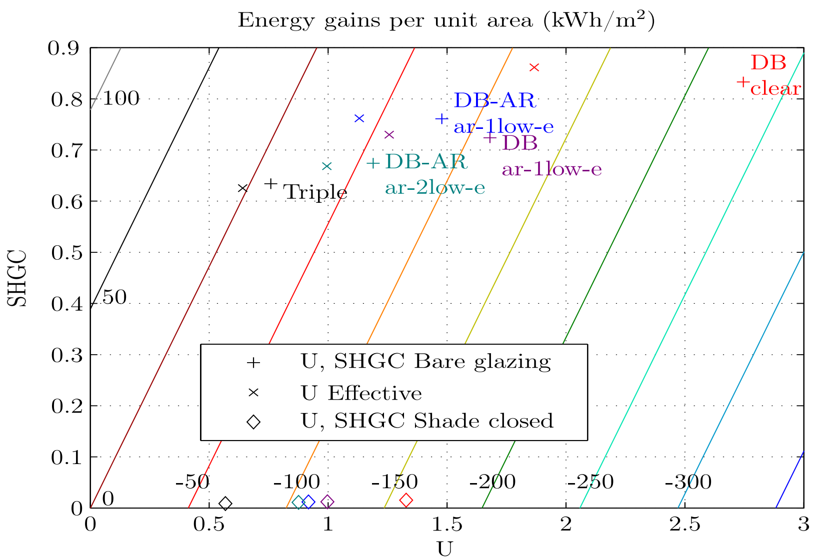


Figure 16: North, with exterior and interior shade

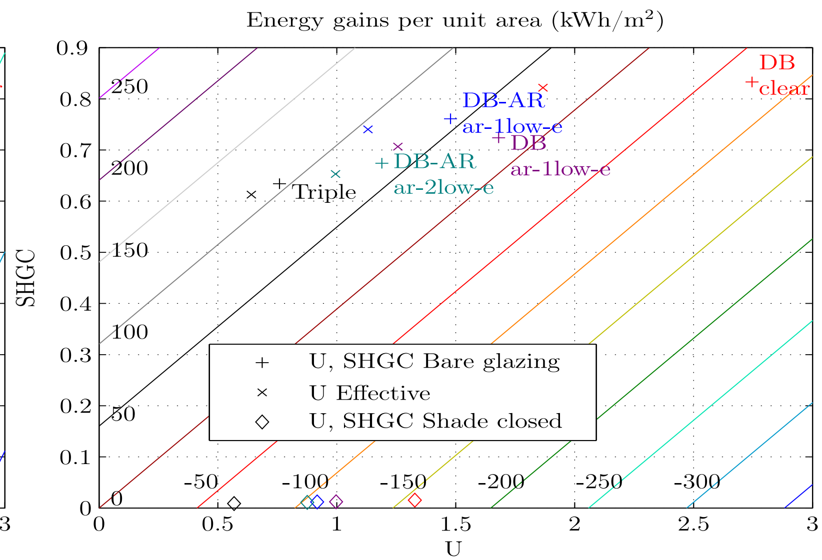


Figure 17: East, with exterior and interior shades

It can be seen on Figure 10 that a conventional roller shade reduces the U-value of a double glazing with argon and low-e from 1.7 to 1.3 when closed, which would significantly improve thermal comfort and could avoid perimeter heating.

5. Experimental comparison and discussion

An experimental test-room was built to study active heat storage with phase change materials in solariums and direct gain rooms with different combinations of interior and exterior shading devices. The purpose of this experiment was to determine experimental U-values of fenestration systems with different shading configurations and compare these values with those obtained with the methodology described in section 2. Since the methodology is employing fixed U-values based on interior and exterior temperatures as defined in NFRC 100-2004 [34] or in ISO 15099 [35], steady-state environmental conditions were provided. Therefore, the presence of thermal storage materials did not influence this specific experiment but was included for future studies about optimization of thermal storage for solariums and greenhouses.

Four different shading devices have been tested under NFRC conditions where the test-room has been installed in a cooling chamber at -18°C and the interior kept at a constant 21°C with an electric heater. Shades properties are listed in Table 4.

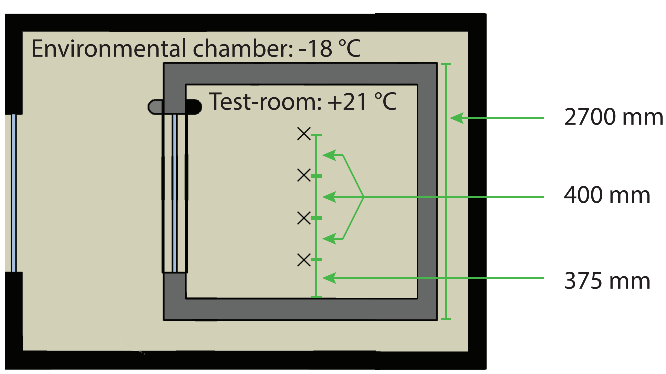


Figure 18: Schematic of the experimental test-room in the environmental chamber showing the configuration with an interior and exterior shades. The X indicates the location of interior thermocouples.

The interior shading material 1 consists of a highly open shade with a high solar transmittance. There was a total opening area of 0.241 m^2 at the shade perimeter between the shade and the glazing. The interior shade 2 is a nonpermeable material that has been fitted tightly on the frame. The exterior shade 1 is made of commercially available polyurethane filled aluminum slats. The exterior shade 2 is a custom made panel made of vacuum insulated panels (VIP) sandwiched between extruded polystyrene (XPS). Its thermal resistance has been evaluated at R 2.19 Km^2/W.

The test-room consists of a chamber 3 m long by 1.5 m wide and 2.7 m high simulating an attached sunspace with a 2 m by 2 m double glazed window (glazing U-value=1.314 $W/(m^2K)$ and SHGC=0.262). The glazing and framing area are 3.64 and 0.493 m^2 respectively while the U-value of the frame is 1.9 $W/(m^2K)$. The overall U-value of the window is 1.7 $W/(m^2K)$. The air tightness of the test-room has been measured at different pressure differential levels by performing blower door testing. The air infiltration at 50 Pa has been evaluated through polynomial regression as 4.1 ACH and the infiltration rate under the tested conditions (-18°C/+21°C) has been estimated as 0.2 ACH.

Four type T thermocouples (accuracy of 0.5°C) were located inside the test-room as shown in Figure 18 and four outside in the climatic chamber. An average temperature difference between the climatic chamber and the test-room of 37.7 °C was maintained during the tests.

The electricity consumption of the heater was monitored for the unshaded test-room and the five different shading configurations described in Table 5. The U-value of the test room attributed to the envelope (walls, ceiling and floor) has been evaluated as 0.35 $W/(m^2K)$. It was calculated from the heater electricity consumption for the unshaded test-room and by subtracting the losses due to the window and infiltration. The experimental U-value of the fenestration system in a given configuration was determined from subtracting the heat losses due to the envelope, window frame and infiltration to the heater electricity consumption. The U-values of the different shade configurations obtained experimentally are compared in Table 5 with values that have been calculated following the methodology presented in this paper.

As can be seen from Table 5, simulated and experimental U-values are relatively close to each other, with simulation results having a general tendency to be lower than experimental values.

The interior shade 1 has a high openness factor of 0.52 while the interior shade 2 is totally impervious to air. It should also be noted that the interior

Table 4: Technical properties of tested shading devices
* The thermal resistance of the interior shades was too low to be measured; a value of 0.01 W/(m^{2}K) has been selected for simulations.

Description	Cavity width cm	τ_s	α_s	ϵ f/b	R Km^2/W	OP	Opening m^2
Int shade 1	15.5	0.77	0.02	0.89	0.01*	0.52	0.241
Int shade 2	9.4	0	0.37	0.49	0.01*	0	0
Ext shade 1	5.4	0	0.28	0.79/0.76	0.080	0	0
Ext shade 2	1.9	0	0.37	0.49	2.19	0	0

Table 5: Comparison of experimental and simulation results - U glazing = 1.314 W/(m^{2}K)

	U-value Simulated W/(m^{2}K)	U-value Experimental W/(m^{2}K)
Configuration		
Window/Int shade 1	1.09	1.18
Window/Int shade 2	0.97	1.04
Ext shade 1/Window	0.99	0.99
Ext shade 2/Window	0.31	0.45
Ext shade 1/Window/Int shade 1	0.86	0.96

shade 2 was installed in an airtight fashion while there were large openings around the interior shade 1. Even with such a large openness factor, openings around the shades and a relatively wide cavity, measurements are showing that the interior shade 1 improves the glazing U-value by 10%. The simulated U-value of the exterior shade 2 is significantly lower than measured. This is probably mainly due to the uncertainty related to the determination of the overall thermal resistance of the shade, which is made of a combination of VIP and EXP, arranged non uniformly in order to cover completely the glazing.

Experimental results might be indicating that the sensitivity to the openness factor and openings area is more important in reality than what is calculated with the ISO 15099 model, but a more thorough experimental validation would be needed to confirm this. It should be noted that there are no restrictions concerning the range of openness factor in ISO 15099.

The most significant uncertainty in the modelling of the heat transfer through fenestration systems probably pertains to the calculation of the convective heat transfer coefficient in the cavity between the glazing and shading layers. Although the algorithm developed in ISO 15099 has been implemented in many important building energy simulation software (EnergyPlus, WINDOW, WIS) and used to conduct comprehensive simulations of various window attachments [11], there is a lack of experimental validation in the published literature to date. A study conducted with diffuse interior and exterior shading screens revealed discrepancies in the ability of various building energy simulation programs to model the heat transfer in the cavity between the shading and glazing layers [23]. The development of a simple yet accurate model or correlation for the determination of the convective cavity heat transfer coefficient is an important area for future research.

The ASHWAT model [43] developed an approximate model that allows the calculation of the impact of the cavity width on the convective coefficients in the vicinity of a shade, based on the two limiting cases (where the shade is far away from a window or where the spacing approaches zero). It is acknowledged that this model is only an approximation and that future research should be conducted regarding the convective heat transfer coefficient in the glazing/shading cavity. The ASHWAT model also developed useful correlations for the determination of solar optical properties of venetian blinds, drapes, screens and roller shades [44, 36, 37, 45]. It should be noted that for the latter, the openness factor must not be higher than 0.2.

Although there has been significant advancement in the last decades in the evaluation of the thermal performance of shading devices, challenges remain due to the complexity of the heat transfer in complex fenestration systems [46]. Should simpler validated physical models or more accurate empirical correlations be developed in the future that better describe the heat transfer through fenestration systems, they could easily replace the equations suggested in this methodology.

6. Conclusion

This paper presented a methodology to help in the selection of fenestration systems for buildings in heating dominated climates. The method has the capability to simulate a one or two layer shading system with one exterior and/or one interior planar shade. This method generates 2D schematics indicating lines of constant net energy gain per unit area as a function of the SHCG and U-value on which different fenestration components are situated. Such graphics are useful in early design stage to compare different design options on a relative basis for a specific orientation and climate.

The essence of the method is based on the computation of the useful solar gains through fenestration and associated heat losses when the exterior temperature is below the balance temperature. This methodology is intended to be used for the design of buildings aiming at a high solar utilization like solar houses, solariums/greenhouses and buildings adopting the *solar optimized fenestration systems* design concept. It has the capability to evaluate the performance of either glazings or complete windows in combination with a one or two layer shading system. Once implemented, this methodology can be readily used for new or retrofit projects in different locations.

This methodology can be used independently or as a preliminary design tool to help identifying the best performing combinations of windows and shades as a function of orientation before running whole building energy simulations.

This paper presented diagrams for glazings equipped with an interior roller shade, an exterior roller shutter and a combination of both for the four cardinal orientations for the city of Montreal, Canada. A comparison of simulated and experimental U-values of four shading devices revealed results relatively close to each other, but additional research on the convective heat transfer coefficient in the cavity between the shading and glazing layers is needed.

Acknowledgements

The first author would like to thank the *Fond de recherche Nature et technologies* for a doctoral scholarship as well as the Smart Net Zero Energy Buildings Strategic Reseach Network and the ecoENERGY Innovation Initiative from Natural Resources Canada for partial support. The invaluable collaboration of Vasken Dermadiros for carrying the experimental work is also gratefully acknowledged.

A. Incident solar radiation calculation and angular profiles

The incident beam solar radiation is computed as

$$I_b = \text{DNR}\, cos(\theta) \tag{34}$$

The diffuse radiation incident on exterior surfaces I_{ds} is modeled according to the approach described in Perez et al. [47]. The ground diffuse solar radiation and total diffuse solar radiation incident on a surface are given by

$$I_{dg} = \text{GHR}\, \rho_{gr}\, F_{i,g} \tag{35}$$

$$I_d = I_{ds} + I_{dg} \tag{36}$$

Table 6: Angular profiles, from [32].

θ	g_1	g_2	g_3
0	1	1	1
5	0.9999	0.9998	0.9997
10	0.9994	0.9992	0.9989
15	0.9987	0.9980	0.9975
20	0.9975	0.9962	0.9954
25	0.9956	0.9936	0.9924
30	0.9928	0.9897	0.9882
35	0.9886	0.9841	0.9825
40	0.9823	0.9758	0.9743
45	0.9728	0.9636	0.9622
50	0.9585	0.9450	0.9436
55	0.9368	0.9162	0.9132
60	0.9034	0.8710	0.8625
65	0.8522	0.8003	0.7789
70	0.7740	0.6927	0.6507
75	0.6564	0.5412	0.4796
80	0.4865	0.3537	0.2905
85	0.2597	0.1592	0.1209
90	0	0	0
	f_1	f_2	f_3
Hemispherical	0.9114	0.8854	0.8748

B. Using the methodology for windows

This methodology can be used for comparing either glazings or complete windows. In this method, it is assumed that the shade(s) (if present) covers only the glazed part of the window and is parallel to the glass. If the window has a frame, it is assumed that the shading device is not covering the frame.

For clarity, equations are presented for glazings only throughout this paper. For users interested in analyzing windows, results can be easily adapted. The window U-value is calculated from the glazing and frame U-values as well as the linear thermal transmittance Ψ :

$$U_w = \frac{\Sigma U_g A_g + \Sigma U_f A_f + \Sigma l_\Psi \Psi}{A_t} \tag{37}$$

where l_Ψ is the vision area perimeter. The summations in equation 37 refer to cases when one particular component does not have uniform properties (different glazings or head/jambs/sill properties). When analyzing windows with this method, it is necessary to know the window U-value, glazing U-value, total window area and glazing area. The contribution of the frame and linear thermal transmittance can be grouped together under the variable Ψ^*:

$$\Psi^* = \Sigma U_f A_f + \Sigma l_\Psi \Psi = U_w A_t - \Sigma U_g A_g \tag{38}$$

The U-value of a shaded window can then be calculated as

$$U_{wS} = \frac{\Sigma U_{gS} A_g + \Psi^*}{A_t} \tag{39}$$

Here it is assumed that the linear thermal transmittance is not affected by the presence of the shade. The SHGC of a bare and shaded window, $SHGC_w$ and $SHGC_{wS}$, are simply computed as follow

$$SHGC_w = \frac{SHGC_g A_g}{A_t} \tag{40a}$$

$$SHGC_{wS} = \frac{SHGC_{gS} A_g}{A_t} \tag{40b}$$

When calculating the net energy gain for windows with equation 14, U_g is replaced by U_w and U_{ExtS} by U_{wS}, where U_{gS} represents the U-value of the shading system under consideration. In addition, $SHGC_g$ and $SHGC_{ExtS}$ are replaced with $SHGC_w$ and $SHGC_{wS}$ from equations 40.

C. Estimating solar transmittance and absorptance

Tables 7-9 were created by selecting glazings with SHGC > 0.5 from the WINDOW database [16] and assembled with cavity widths of 12.7 mm. 37 glasses have been selected for Table 7. Correlations from Table 8 and 9 have been derived from 16 glasses assembled in 48 and 80 configurations.

Table 7: Estimated solar transmittance and absorptance - single glazing $h_o = 20$ W/(m^{2}K) - Glazings with U<4 W/(m^{2}K) have low-e on surface #2.

U	SHGC	τ_s	α
U> 5.7	SHGC>0.90	SHGC-0.0035	$\frac{h_o}{U}(SHGC-\tau_s)$
	0.80<SHGC<0.90	SHGC-0.0205	$\frac{h_o}{U}(SHGC-\tau_s)$
	0.645<SHGC<0.80	SHGC-0.1000	$\frac{h_o}{U}(SHGC-\tau_s)$
	0.5<SHGC<0.645	SHGC-0.1315	$\frac{h_o}{U}(SHGC-\tau_s)$
U<4	SHGC>0.635	SHGC-0.0239	$\frac{h_o}{U}(SHGC-\tau_s)$
	0.5<SHGC<0.635	SHGC-0.0500	$\frac{h_o}{U}(SHGC-\tau_s)$

Table 8: Estimated solar transmittance and absorptances - double glazing h_i=8 W/(m^{2}K), h_o=25 W/(m^{2}K) - When present, low-e is on surface #3.

U	SHGC	τ_s	α_1	α_2
Air				
U> 2.7	SHGC>0.82	SHGC-0.0097	$\frac{SHGC-\tau_s+0.0027(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	-0.0027+α_o
	0.80<SHGC<0.82	SHGC-0.0285	$\frac{SHGC-\tau_s+0.0090(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	-0.0090+α_o
	SHGC<0.80	SHGC-0.0467	$\frac{SHGC-\tau_s+0.0167(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	-0.0167+α_o
1.79<U<2.7	all SHGC	SHGC-0.1173	$\frac{SHGC-\tau_s-0.0881(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	0.0881+α_o
1.60<U<1.79	all SHGC	SHGC-0.0813	$\frac{SHGC-\tau_s-0.0427(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	0.0427+α_o
Argon				
U>2.5	SHGC>0.82	SHGC-0.010	$\frac{SHGC-\tau_s+0.0025(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	-0.0025+α_o
	0.75<SHGC<0.82	SHGC-0.0396	$\frac{SHGC-\tau_s+0.0136(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	-0.0136+α_o
1.50<U<1.80	all SHGC	SHGC-0.1131	$\frac{SHGC-\tau_s-0.0878(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	0.0878+α_o
1.36<U<1.50	all SHGC	SHGC-0.0859	$\frac{SHGC-\tau_s-0.0488(h_i-U)/h_i}{U/h_o+(h_i-U)/h_i}$	0.0488+α_o

Table 9: Estimated solar transmittance and absorptance - triple glazing h_i=7 W/(m^{2}K), h_o=26 W/(m^{2}K) - When present, low-e is on surface #5 or on surfaces #3 and #5.

U	SHGC	τ_s	α_1	α_2	α_3
Air					
U> 1.7	SHGC>0.75	SHGC-0.0157	0.0160	0.0021+α_3	$\frac{0.0157-\alpha_1 U/h_o-0.0021U(h_o^{-1}+0.1645)}{U(h_o^{-1}+0.1645)+(h_i-U)/h_i}$
	SHGC<0.75	SHGC-0.0586	0.0646	0.0104+α_3	$\frac{0.0586-\alpha_1 U/h_o-0.0104U(h_o^{-1}+0.1645)}{U(h_o^{-1}+0.1645)+(h_i-U)/h_i}$
1.15<U<1.4	all SHGC	SHGC-0.1016	0.0500	-0.0628+α_3	$\frac{0.1016-\alpha_1 U/h_o+0.0628U(h_o^{-1}+0.1645)}{U(h_o^{-1}+0.1645)+(h_i-U)/h_i}$
1<U<1.15	all SHGC	SHGC-0.1433	0.0515	0.0585+α_3	$\frac{0.1433-\alpha_1 U/h_o-0.0585U(h_o^{-1}+0.1645)}{U(h_o^{-1}+0.1645)+(h_i-U)/h_i}$
U<1	all SHGC	SHGC-0.1144	0.0515	0.0585+α_3	$\frac{0.1144-\alpha_1 U/h_o-0.0585U(h_o^{-1}+0.3154)}{U(h_o^{-1}+0.3154)+(h_i-U)/h_i}$
Argon					
U> 1.6	SHGC>0.75	SHGC-0.0160	0.0160	0.0021+α_3	$\frac{0.0160-\alpha_1 U/h_o-0.0021U(h_o^{-1}+0.1878)}{U(h_o^{-1}+0.1878)+(h_i-U)/h_i}$
	SHGC<0.75	SHGC-0.0588	0.0646	0.0104+α_3	$\frac{0.0588-\alpha_1 U/h_o-0.0104U(h_o^{-1}+0.1878)}{U(h_o^{-1}+0.1878)+(h_i-U)/h_i}$
0.96<U<1.3	all SHGC	SHGC-0.1029	0.0500	-0.0628+α_3	$\frac{0.1029-\alpha_1 U/h_o+0.0628U(h_o^{-1}+0.1878)}{U(h_o^{-1}+0.1878)+(h_i-U)/h_i}$
0.78<U<0.96	all SHGC	SHGC-0.1460	0.0515	0.0585+α_3	$\frac{0.1460-\alpha_1 U/h_o-0.0585U(h_o^{-1}+0.1875)}{U(h_o^{-1}+0.1875)+(h_i-U)/h_i}$
U<0.78	all SHGC	SHGC-0.1168	0.0515	0.0585+α_3	$\frac{0.1168-\alpha_1 U/h_o-0.0585U(h_o^{-1}+0.4185)}{U(h_o^{-1}+0.4185)+(h_i-U)/h_i}$

Table 10: Average and maximum error.

		τ_s	α_1	α_2	α_3
Single glass	Average error	0.007	0.027	-	-
	Maximum error	0.034	0.080	-	-
Double glass	Average error	0.012	0.020	0.014	-
	Maximum error	0.070	0.046	0.051	-
Triple glass	Average error	0.012	0.023	0.018	0.013
	Maximum error	0.048	0.046	0.041	0.066

References

[1] Natural Resources Canada, . Comprehensive energy use database. 2015. URL http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensiv

[2] Tzempelikos, A., Athienitis, A.K., Karava, P.. Simulation of façade and envelope design options for a new institutional building. Solar Energy 2007;81(9):1088–1103.

[3] Ochoa, C.E., Aries, M.B.C., van Loenen, E.J., Hensen, J.L.M.. Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. Applied Energy 2012;95:238–245.

[4] Lee, J.W., Jung, H.J., Park, J.Y., Lee, J.B., Yoon, Y.. Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. Renewable Energy 2013;50:522–531.

[5] Koo, C., Park, S., Hong, T., Park, H.S.. An estimation model for the heating and cooling demand of a residential building with a different envelope design using the finite element method. Applied Energy 2014;115:205–215.

[6] Huang, Y., Niu, J.l., Chung, T.m.. Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. Applied Energy 2014;134:215–228.

[7] Hee, W., Alghoul, M., Bakhtyar, B., Elayeb, O., Shameri, M., Alrubaih, M., et al. The role of window glazing on daylighting and energy saving in buildings. Renewable and Sustainable Energy Reviews 2015;42:323–343.

[8] CMHC, . Energy Audits of High-Rise Residential Buildings. Tech. Rep.; Canadian Mortgage and Housing Corporation; 1996.

[9] Proskiw, G.. Identifying affordable net zero energy housing solutions. CanmetENERGY, Natural Resources Canada 2010;.

[10] Karlsson, J., Roos, A.. Annual energy window performance vs. glazing thermal emittance - The relevance of very low emittance values. Thin Solid Films 2001;392(2):345–348.

[11] Curcija, C., Yazdanian, M., Kohler, C., Hart, R., Mitchell, R., Vidanovic, S.. Energy Savings from Window Attachments. Lawrence Berkeley National Laboratory, DOE/EE-0969 2013;:102.

[12] Schumman, J., Lee, E.S., Rubinstein, F.M., Selkowitz, S.E., Robinson, A.. Tips for daylighting with windows: The integrated approach. Tech. Rep.; Lawrence Berkeley National Laboratory; 2013.

[13] Tzempelikos, A.. A methodology for integrated daylighting and tharmal analysis of buildings. Phd; Concordia University; 2005.

[14] Tzempelikos, A., Athienitis, A.K.. The impact of shading design and control on building cooling and lighting demand. Solar Energy 2007;.

[15] Nielsen, M.V., Svendsen, S., Jensen, L.B.. Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. Solar Energy 2011;85(5):757–768.

[16] LBNL, . THERM 6.3 / WINDOW 6.3 NFRC Simulation Manual. Lawrence Berkeley National Laboratory, CA 2014;.

[17] LBNL, . RESFEN 5.0 User's Manual. Lawrence Berkeley National Laboratory 2005;.

[18] WinDat, . WIS Version 3.0.1 Help file - converted to pdf document. Window Energy Data Network 2004;.

[19] Lund University, . ParaSol 6.6. 2010. URL `http://www.ebd.lth.se/program/parasol/`.

[20] US DOE, . EnergyPlus Engineering Reference. US Department of Energy 2013;.

[21] Klein, S.A., al., E.. TRNSYS 17: A transient system simulation program. Solar Energy Laboratory, University of Wisconsin, Madison, USA 2010;URL `http://sel.me.wisc.edu/trnsys`.

[22] ESR U, . ESP-r 11.11. Energy Systems Research Unit, University of Strathclyde, Glasgow 2011;.

[23] Loutzenhiser, P., Manz, H., Maxwell, G.. Empirical validations of shading/daylighting/load interactions in building energy simulation tools. IEA SHC Task 34/ECBCS Annex 43 Project C 2007;:177.

[24] Tzempelikos, A.. A review of optical properties of shading devices. Advances in Building Energy Research 2008;2(1):211–239.

[25] Rogalsky, C.. Application of a network solution to complex fenestration systems. Master thesis; University of Waterloo; 2011.

[26] Nielsen, T., Duer, K., Svendsen, S.. Energy performance of glazings and windows. Solar Energy 2001;69(1):137–143.

[27] Hviid, C.A., Nielsen, T.R., Svendsen, S.. Simple tool to evaluate the impact of daylight on building energy consumption. Solar Energy 2008;82(9):787–798.

[28] Nielsen, T.R.. Simple tool to evaluate energy demand and indoor environment in the early stages of building design. Solar Energy 2005;78(1):73–83.

[29] Orsi, A.. An exploration of the impact of fixed shading device geometry on building energy performance. Master; Michigan State University; 2009.

[30] US DOE, . EnergyPlus Energy Simulation Software - Weather Data. US Department of Energy 2015;:2013–09–09URL http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm.

[31] Finlayson, E., Arasteh, D., Huizenga, C., Rubin, M.. Window 4.0: Documentation of calculation procedures. Lawrence Berkeley National Laboratory, CA 1993;.

[32] Karlsson, J., Rubin, M., Roos, A.. Evaluation of predictive models for the angle-dependent total solar energy transmittance of glazing materials. Solar Energy 2001;71(1):23–31.

[33] ASHRAE, . ASHRAE Handbook - Fundamentals 2009;.

[34] NFRC 100-2004, . Procedure for determining fenestration product U-factors. National Fenestration Rating Council 2004;:81.

[35] ISO 15099, . Thermal performance of windows, doors and shading devices - Detailed calculations 2003;.

[36] Kotey, N.A., Wright, J.L., Collins, M.R.. Determing off-normal solar optical properties of insect screens. ASHRAE Transactions 2009;115(1):10.

[37] Kotey, N.A., Wright, J.L., Collins, M.R.. Determining off-normal solar optical properties of roller blinds. ASHRAE Transactions 2009;115(1):10.

[38] ISO 10292, . Glass in building - Calculation of steady state U value (thermal transmittance) of multiple glazing 1994;.

[39] Bülow-Hübe, H.. Energy-efficient window systems : effects on energy use and daylight in buildings. Phd; Lund University; 2001.

[40] Carmody, J., Selkowitz, S., Heschong, L.. Residential windows: a guide to new technologies and energy performance. New York: W.W. Norton & Company; 2nd editio ed.; 2000.

[41] Athienitis, A.K., Liu, C., Hawes, D., Banu, D., Feldman, D.. Investigation of the thermal performance of a passive solar test-room with wall latent heat storage. Building and Environment 1997;32(5):405–410.

[42] O'brien, W.. Development of a solar house design methodology and its implementation into a design tool. Phd; Concordia University; 2011.

[43] Wright, J.L., Collins, M.R., Kotey, N.A., Barnaby, C.S.. Improving Cooling Load Calculations for Fenestration with Shading Devices. ASHRAE 1311-RP 2009;30329(404):95.

[44] Kotey, N., Collins, M., Wright, J.L., Tiang, T.. A simplified method for calculating the effective solar optical properties of a venetian blind layer for building energy simulation. Journal of Solar Energy Engineering 2009;131(2):9.

[45] Kotey, N.A., Wright, J.L., Collins, M.R.. Determining off-normal solar optical properties of drapery fabrics. ASHRAE Transactions 2009;115(2):15.

[46] Laoudi, A.. Thermal modeling of shading devices of windows. ASHRAE Transactions 2009;115(2):1–20.

[47] Perez, R., Ineichen, P., Seals, R., Michalsky, J., Stewart, R.. Modeling daylight availability and irradiance components from direct and global irradiance. Solar Energy 1990;44(5):271–289.

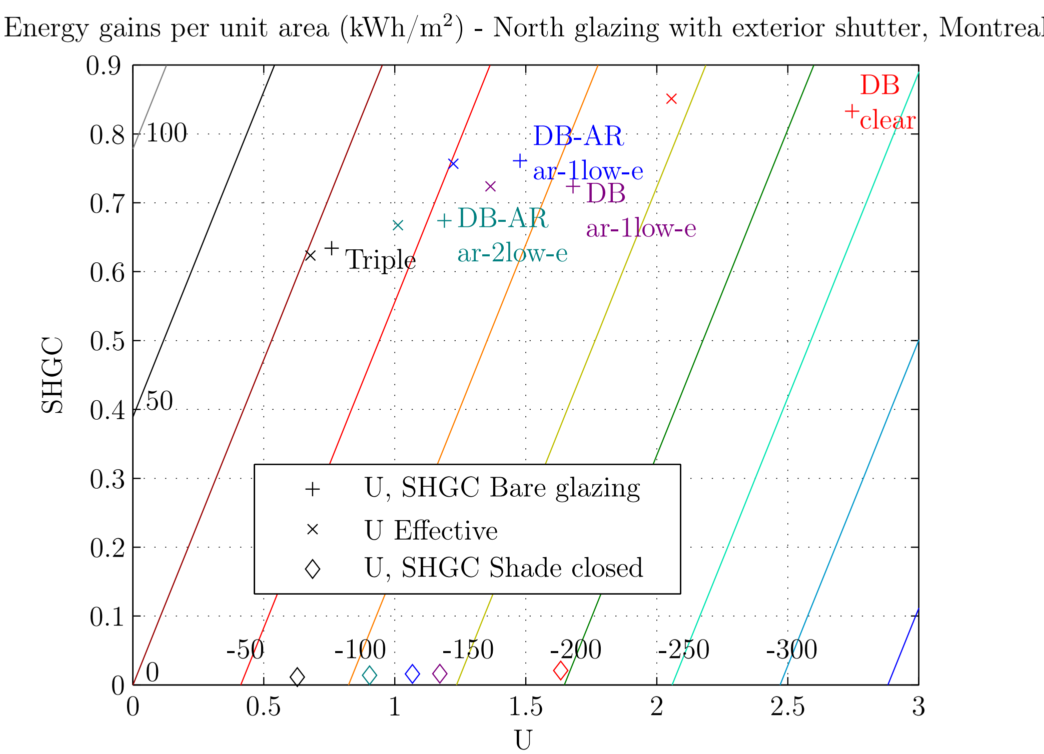


Figure 19: Graphical abstract