Modeling and Daylighting Design of a New Window with Integrated Controllable

Louver System

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Abstract

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Highly glazed building façades are increasingly popular in contemporary architecture, and as a result, new solar control technologies incorporated into advanced fenestration products are moving towards improved daylighting performance and more effective control of solar heat gain. Integrating advanced fenestration products into a building's façade design is considered as an effective way to conserve energy in commercial buildings.

An advanced fenestration product, known as VisionControl®, integrates controllable aluminum louvers between two panes of glass, and is currently available on the market. This study starts by redesigning the VisionControl® window to reduce its overall thickness in order to enable its applications in commercial curtain walls and retrofit projects. The three-section façade concept is widely used in the commercial curtain wall industry as it provides view and daylight while controlling solar heat gain. This thesis presents a mathematical daylighting model developed based on a three-section curtain wall façade with the newly designed VisionControl® window installed on both the top and middle sections. The model represents separately the two window sections so that the middle and top section louvers can be independently controlled to maximize daylight transmission in the room while avoiding glare. This model is capable of estimating the workplane illuminance with the consideration of several important design

parameters, such as building location, façade orientation, control strategy and window materials.

Two experiments were conducted for this study. The visible transmittance of the newly designed VisionControl® window was measured in the first experiment. A custom-built testing device was designed to obtain accurate visible transmittance results with the consideration of different solar profile angles and louver tilt angles. Another experiment was conducted with a small scale office model to validate the mathematical daylighting model. Experimental results were compared with model-calculated results under three representative sky conditions. This comparison confirmed that the daylighting model can be utilized to estimate workplane illuminance with the newly designed VisionControl window with reasonable accuracy.

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Nomenclature

A _i	Area of surface i, m^2
C _{i-s1}	Configuration factor from the i-th sensor point to surface 1
C _i	Configuration factor from the i-th sensor point to all room surfaces in matrix format
D _{rm}	Depth of office room, m
DA	Daylight autonomy
E	Illuminance on exterior façade surface, lux
Ei	Emissivity of surface i
Eworkplane_i	Final workplane illuminance due to daylight at the i-th sensor point
F _{ij}	View factor between surface i and j
F	View factor in matrix format
H _{rm}	Height of office room, m
H _{top}	Height of the top section of the three-section façade, m
H _{mid}	Height of the middle section of the three-section façade, m

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Mo

Height of the spandrel section of the three-section façade, m

Initial luminance exitance of all interior surfaces in matrix format, lux

 M_{top}

 M_{mid}

M_{final}

ŀ

Ibeam

VT

W

Initial luminance exitance on the top section of the three-section façade, lux

Initial luminance exitance on the middle section of the threesection facade, lux

Final luminance exitance of all interior surfaces in matrix format, lux

Moment of inertia, kg*m²

Direct beam irradiance, Watt/m²

UDI Useful daylight illuminance

Visible transmittance of VisionControl® window

Louver's own weight, kg

W_{rm} Width of office room, m

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Greek letters

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,

α	Solar altitude angle
β	Louver tilt angle
γ	Surface solar azimuth angle
δ	Solar declination
λ	Solar profile angle
ρ	Reflectivity of surfaces in matrix format
ρ _i	Reflectivity of surfaces i
τ	Window visible transmittance
τ_{direct}	Direct transmittance of the window
$ au_{diffuse}$	Diffuse transmittance of the window
τ_{top}	Visible transmittance of the top section of the three-section façade
$ au_{mid}$	Visible transmittance of the middle section of the three-section
	façade
$\Omega_{ ext{cut-off}}$	Direct sunlight cut-off angle
Δ_{\max}	Maximum deflection at middle point of a louver span, m

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Chapter 1: INTRODUCTION

1.1 Background

In Canada, offices and other institutional buildings use about 35% of the energy consumed by the commercial sector and lighting represents a major energy-user in these buildings – around 9% (NRCan 2009). Based on 2008 Buildings Energy Data Book from U.S. Department of Energy, residential and commercial buildings in U.S. use 74.2% of the electricity in 2006 and this number is expected to rise to 76.5% by 2025 (U.S Department of Energy 2008). Developing innovative technologies to reduce energy consumption in artificial lighting systems, by integrating systematic daylighting use, is considered as an effective way to conserve energy in commercial buildings.

Highly glazed building façades are increasingly popular for commercial buildings as they provide daylight into the space, enhanced visual contact with the exterior environment and a feeling of openness, improving occupants' productivity and level of satisfaction (Galasiu and Veitch 2006). The increased use of glass in contemporary architecture is driving building designers, owners and occupants to demand higher performing window and shading products than ever before. Several recent developments in window industry, such as advanced fenestration products and solar control coatings, have demonstrated the potential for creating more energy-efficient curtain wall façades.

Shading devices are usually installed with curtain wall façades to protect the interior space from glare and excessive solar heat gain. Compared to the window industry, the shading device industry has produced fewer innovations in the past decades. Many newly constructed commercial buildings with curtain wall façades are still equipped with conventional roller blinds or venetian blinds. These types of conventional

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shading devices can no longer meet the increasing demand for better daylighting performance from building designers and occupants.

Building designers must be aware that in order to achieve higher energy efficiency in curtain wall designs, the energy performance of the entire curtain wall façade system depends on not only the Insulated Glazing Unit (IGU), the shading device or the control, but on the three in combination.

1.2 Motivation

Curtain wall façade design is often limited by the available commercial window products and shading devices. New advanced fenestration products have been developed which are intended to improve illumination quantity and quality while managing radiant solar heat gain to meet both human comfort and energy conservation objectives (Mccluney 1998). Unicel Architectural Corp. has a long history of collaboration with Concordia University which have resulted in several publications and theses (Tzempelikos 2002), (Park and Athienitis 2003). This company has a patented advanced fenestration product (as shown in Figure 1-1), known as VisionControl®, which integrates aluminum venetian blinds between two panes of glass. As opposed to conventional venetian blinds, which use cords to operate slats, the VisionControl® window utilizes a patented pivot design which provides accurate and smooth control of louver tilt with both manual and motorized operations available. This unique design provides an Insulating Glass Unit (IGU) and aluminum venetian blinds as a package, providing extra features such as minimal installation costs and low maintenance.



Figure 1-1 VisionControl® window

One major limitation of the old generation of VisionControl® window is that its 2.5" overall thickness (including two panes of ¼" glazings) excludes it from standard curtain wall constructions and retrofit projects. The overall thickness of the product needs to be reduced before it can be widely used in the construction industry. For this reason, a joint research project was launched in January, 2008 between Concordia University and Unicel Architectural Corp to develop a new generation of the VisionControl® window.



Figure 1-2 Integration of VisionControl® window with three-section façade concept for curtain wall façade design

Tzempelikos (2002) studied the energy saving potential of an office with a single unit of the old generation of the VisionControl® window installed. His study concluded that by using the old generation of the VisionControl® window, energy savings from reduced utilization of electric lights and internal heat gain can be achieved. This study expanded on Tzempelikos's work by integrating the newly designed VisionControl® window into a three-section curtain wall façade design (as shown in Figure 1-2), which will further enhance the performances in daylighting and controlling solar heat gain. This type of façade sign can provide the following benefits:

- Direct sunlight can be blocked easily by the integrated aluminum louvers in a wide louver tilt range. Glare caused by direct sunlight can be reduced.
- 2. The position of the louvers in the top daylighting section can be controlled to maximize daylight transmittance, reflect the daylight towards the ceiling, and illuminate the deeper part of the interior.

- 3. The position of the louvers in the middle viewing section can be controlled to maximize view to the exterior with the prerequisite that no direct sunlight be allowed to penetrate the window.
- 4. Top and middle sections of the façade can be controlled independently to meet different needs of the occupants, such as closing up the middle section for privacy or both sections for a video presentation.
- 5. The VisionControl® window can be motorized so any future development of advanced control strategies for this three-section façade design can be implemented easily.

The use of advanced fenestration products in commercial curtain wall façades is rare. Integrating the VisionControl® window with three-section curtain wall façade concept is a new idea for the curtain wall industry. The number of studies that are related to advanced fenestration products especially regarding daylighting is quite limited. Due to the complexity of advanced fenestration products, investigating their daylighting performance is a difficult task. In order to facilitate the use of new advanced fenestration products in new building façade designs and retrofits projects, a mathematical daylighting model is considered useful for both research and design.

1.3 Thesis objectives

The objectives of this thesis are to:

- Develop a new design concept for a window with integrated blinds so to reduce the product's overall thickness from 2.5" to 1.5" and to incorporate a new louver profile. The newly designed louver should facilitate interior daylight distribution.
- Study the daylighting performance of integrating the three-section façade concept with a newly designed advanced fenestration product – VisionControl® window
- 3. Develop a mathematical daylighting model for the studied three-section façade with VisionControl® window to provide estimation of workplane illuminance. This mathematical model should be able to consider important design parameters such as building location, façade orientation, geometry of the three-section curtain wall façade and control strategy.
- 4. Measure the visible transmittance of the newly designed VisionControl® window as it is one of the most important inputs for the development of the mathematical model. The measurements should consider the impact from different sky conditions, solar profile angles and louver tilt angles.
- 5. Conduct an experimental study to validate the mathematical model. Experimental results will be compared with the model-calculated results under clear, intermediate and overcast sky conditions.

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1.4 Overview of thesis

Chapter 2 presents an overview of research conducted in the design and daylighting performance study of several advanced fenestration products. A review of advanced fenestration products available on the market is also conducted and benefits/features provided by each product are compared. Chapter 3 presents the mathematical daylighting model of the three-section façade concept with the newly designed VisionControl® window. Chapter 4 presents the experiment for measuring the visible transmittance of the newly designed VisionControl[®] window. Experimental setup, methodology and results are described. Chapter 5 describes the experiment conducted to verify the mathematical daylighting model. Simulation results are compared with experimental results and relative errors are discussed. Chapter 6 presents several simulations were conducted for a typical office in different building locations, façade orientations and control strategies. Results are compared to illustrate the potential of the mathematical model for future application in curtain wall façade design. Finally, conclusions and recommendations for future research are summarized in Chapter 7. The author played a key role in the design of the new generation of VisionControl® window. The description of the new louver design in Appendix A is an example to explain the design considerations and strategies used during the development of the new product.

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Chapter 2: LITERATURE REVIEW

2.1 Introduction

As part of the effort to reduce green-house gas emissions, office buildings ought to consume less energy (Galasiu and Veitch 2006). In Canada, offices and other institutional buildings use about 30% of the energy consumed by the commercial sector and lighting represents a major energy-user in these buildings (around 15%) (NRCan 2009). Large amounts of energy can be saved by using well designed lighting controls that can take advantage of the natural light available (Bourgeois et al. 2006). During the conceptual design stage of a building, the design team often has to make critical decisions with significant impact on the energy performance and indoor comfort conditions (Tzempelikos et al. 2007).

2.2 Daylight in buildings

Daylighting is the design of buildings to use visible light from the sun to illuminate the interior (Leslie 2003). In terms of luminous efficacy (lm/w), sunlight is more efficient than the majority of artificial lighting used in commercial buildings and it has a richer spectral distribution to which our eyes have evolved (Kapsis 2009).

It is important to realize that daylighting is not only an energy-efficiency technology, but also a major factor in occupants' perception and acceptance of workspaces in buildings (Reinhart et al. 2006). Successful energy savings from daylighting can only be realized when the building and systems design support broader occupant needs for comfortable and healthy indoor environments (Reinhart and Selkowitz 2006).

Cuttle (1983) administered questionnaires in England and New Zealand to investigate the perceived attributes of windows. In 471 office workers investigated in the study, almost all respondents (99%) thought that offices should have windows and 86% considered daylight to be their preferred source of lighting. The preference for daylight was attributed to the belief that working by daylight results in less stress and discomfort that working by electric light.

University students in Canada were surveyed by Veitch et al. (1993). Between 65 and 78% of the sample endorsed statements about the superiority of natural light, such as "natural daylighting is better for working under than artificial light". The averaged daylight beliefs correlated moderately with "lighting effects on health" and "superiority of natural light over other types". Wells (1965) interviewed office workers on the floors of an open, deep-plan office building with glass curtain walls located in UK. 89% of the subjects felt that a view out was very important and 69% felt that it was better for their eyes to work by daylight than by electric light. This study concluded that "people's estimates about what they think they need in terms of daylight and view out are independent of the actual physical environment and the presence of daylight..."

From these studies, it is clear that in spite of daylight's superiority in terms of human health, activity and potential in reducing energy demand, introducing daylight into buildings without proper control could also cause problems in thermal comfort, high cooling load and glare.

2.3 Shading devices

Shading devices have long been used to control solar gain and daylight through windows. Conventional shading devices can be categorized as interior or exterior shadings. Interior shadings, such as roller blinds, venetian blinds and curtains, and exterior shadings, such as lightshelves and louver systems, are widely used with windows and transparent façades. Driven by the technological advances in transparent building façades, design alternatives have shifted to utilizing dynamic fenestration and shading systems for optimal control of daylighting and solar gains (Tzempelikos et al. 2007). Kuhn et al. (2001) summarized important requirements for sun-shading systems as illustrated in Figure 2-1.



Figure 2-1 User requirements for sun-shading systems (Kuhn et al. 2001)

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2.4 Control strategies for shading devices

Today, control strategies are still an active topic in the daylighting research field. Kuhn et al. (2001) pointed out the importance of control strategy by saying that "it is the starting point of shading device performance assessment". The ultimate objective of using shading device is to provide a comfortable environment for occupants. Occupant behavior is an important aspect for studying control strategies for shading devices.

2.4.1 Impacts of human behavior

Rubin et al. (1978) found that most occupants of perimeter offices equipped with venetian blinds preferred blind configurations that had little to do with the sun position of the daily and seasonal climatic conditions. Following on Rubin's work, Rea et al. (1984) found that the position of the blinds did not change throughout the day and the occupant most likely changed the position of the blind when direct sunlight reaches the work area, but seldom changed the setting for view or daylight. Another survey conducted by Rea et al. (1998) with 58 US offices also confirmed previous findings – the blinds were usually pulled down as soon as the sun created glare and thermal discomfort, and they were kept down for long periods of time even after these conditions ended.

These findings show that manually operated shading devices provide the flexibility for occupants to choose what they want, but are commonly misused. Reinhart (2004) concluded that "manual control is more of a stochastic nature when considering lighting and blind control".

2.4.2 Automated control strategies

Closed-loop control, also called feedback control, is a type of control which computes its input into a system based on both current state and the feedback of the system (Kuo and Golnaraghi 2003). Closed-loop systems are the most prevalent type of control applications for venetian blinds (O'Neill 2008).

Photocontrolled blinds have been introduced to offset the limitations of manually controlled blinds. Theoretically, the benefit from the use of a photocontrolled blind system arises from the fact that blinds close automatically when glare or overheating become a problem, and re-open later to admit useful daylight (Galasiu et al. 2004). From the studies that have been done on investigating automated control strategies of shading devices, occupants' responses in terms of acceptance and preference are important.

Inoue et al. (1988) studied a questionnaire with 800 workers in two high-rise buildings. The results showed that 60% of the occupants thought the automatic blinds were a valuable addition to the office environment, while 10% were against it. The most common reason for dislike the automated control system is: "the blinds operate even when it is not required". Many people were annoyed because the blinds were perceived to operate at the wrong time. This finding also confirmed that the presence of controls to override the automatic settings was seen as essential by most occupants.

Reinhart and Voss (2003) confirmed the need of override mode in automated control system. 45% of the automated controlled blinds were re-adjusted and switched to override mode. This study also found that occupants mostly accepted the automatic lowering of the blinds only when the illuminance on the façade of the building rose above 50 klux.

From these studies, it can be concluded that controlling the blinds according to a specific workplane or façade surface illuminance setting would cause frequent adjustment of the blind position which annoys occupants. For three-section façade, purpose-

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optimized automated control, such as maximization of the visible transmittance for the top section and maximization of view to exterior for middle section, would cause much less adjustment of blinds. Kuhn et al. (2001) studied two different purpose-optimized control strategies:

- Strategy 'Closed': the blind is fully extended and the slats are completely closed whenever the façade is irradiated directly by the sun. This strategy ignores the need for visual contact to the exterior.
- Strategy 'cut-off': when the sun is shining directly on the façade, the slats are tilted into the cut-off position. The tilt angle of the venetian blinds is determined by the profile angle of the sun (see Figure 3-5).

These two control strategies emphasize the control of direct sunlight and minimize the movement of blind systems, but sacrifice the view to the exterior. Higher acceptance of the automated control system can be achieved by providing a comfortable environment without frequent adjustment of the blind system.

2.5 Advanced fenestration products

New advanced fenestration products have been designed to improve illumination quantity and quality while managing radiant solar heat gain to meet both human comfort and energy conservation objectives (Mccluney 1998). Selkowitz and Lee (1998) also defined advanced fenestration systems as the products which are designed to maximize the energy-saving potential of daylighting, while improving comfort and visual performance at an 'affordable' price. Although studies related to advanced fenestration products are limited, the better performance in daylighting and controlling solar heat gain offered by these new products are expected to facilitate study of improved control strategies and techniques.

2.5.1 Transmittance measurement of advanced fenestration product

The transmittance of VisionControl® window is highly dependent on the solar angles due to the presence of the rotatable slats and specially designed slat profile. Breitenbach et al.(2001) foresaw the importance of obtaining detailed optical and thermal properties of new advanced fenestration products before they can be integrated into good building design. In particular, the variation of performance as a function of angle of incidence of solar radiation is needed to predict their effect on a building's annual energy needs.

The Bi-directional Transmission Distribution Function (BTDF) is able to provide accurate evaluation of daylight distribution through advanced fenestration systems (complex glazing, solar shading systems) (Andersen 2002). Andersen et al. (2005) measured BTDF of an advanced fenestration product with specularly reflective louvers integrated between glass panes (as shown in Figure 2-2). The measurement was conducted with a goniophotometer and the measured results were compared with results generated by a commercial ray-tracing software. Due to the fact that the advanced fenestration studied was a static product (the louver could not be rotated), it is practical to use BTDF. However, for advanced fenestration products with rotatable louvers, the BTDF method becomes unsuitable because the BTDF for each louver tilt angle should be determined.

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Figure 2-2 Venetian blind used in advanced fenestration system (Andersen et al. 2005)

Breitenbach et al. (2001) measured the transmittance of two types of advanced fenestration product with integrated venetian blinds using the Cardiff goniospectrometer (as shown in Figure 2-3). It consists of a light source, an adjustable sample holder, a light collection system and is capable of collecting angle and wavelength dependent optical properties of fenestration systems in a single measurement. Measurements under different slat angles and light source rotation angles were conducted. Sample results plotted in 3D-surface and contour-type figures are illustrated in Figure 2-4.



Figure 2-3 The Cardiff goniospectrometer used for the transmittance measurements of advanced fenestration product



Figure 2-4 sample transmittance results measured by the Cardiff goniospectrometer (plotted in both 3D-surface type and contour type figures) (α is surface azimuth angle and β is incident angle)

Tzempelikos (2002) measured the visible transmittance of the VisionControl® window (old generation) during his study. Figure 2-5 shows that only one photometric sensor was installed behind the window to measure the transmitted illuminance. However, one sensor is considered insufficient to measure detailed daylight distribution between two adjacent louvers. Under clear sky conditions, the sensor could be shaded by

certain louver tilt angles and direct sunlight could penetrate without being measured. Figure 2-6 illustrates the results of the measured visible transmittance of the studied window. It can be seen that the maximum transmittances for different incident angles appear at the same blind tilt angle. This confirms that having only one sensor behind the window is not sufficient to measure accurate transmitted illuminance.



Figure 2-5 Transmitted illuminance measured by a single photometric sensor (Tzempelikos 2002)



Figure 2-6 Daylight transmittance as a function of louver tilt angle for different incident angles (Tzempelikos 2002)

2.5.2 Daylighting performance of advanced fenestration product

Greenup and Edmonds (2004) studied an advanced fenestration product with a micro-light guiding shade (as illustrated in Figure 2-7). This device was created to utilize direct sunlight while maintaining visual and thermal comfort in buildings. The author conducted both experiments and computer lighting simulations to assess the device's performance in terms of effectiveness, efficiency, cost and construction issues. This study concluded that the interior natural illumination provided by this device is more comfortable than the light in a space without the device. At the end of this study, the author suggested that conducting both experimental and simulation work is the best method of refining the design parameters of advanced fenestration products.



Figure 2-7 Micro-reflecting elements of the micro-light guiding shade

Two new sun-shading systems, as shown in Figure 2-8, were developed by Kuhn (2006). In this study, angle-dependent transmittance of the two shading systems was measured under different tilt and solar profile angles. Although the new approach developed by this study is used to model solar gains through the façade, the idea of using an angle-dependent performance indicator (such as g value used in this study) can also be generalized to other daylighting performance studies.



Figure 2-8 Two new sun-shading systems (Kuhn 2006)

2.5.3 Available advanced fenestration products on the market

A review of available advanced fenestration products, daylighting louver systems on the market and the comparison with VisionControl® window, give us a clear idea of how VisionControl® fits into this competitive market. This review summarizes the advantages and disadvantages of these commercial products compared to the VisionControl® window, and important information can be extracted for the design of the new generation of the VisionControl® window.
RetroLux® from RetroSOLAR (www.retrosolar.com)

RetroLux® is an advanced solar control and daylighting venetian blind system from a German company called RetroSOLAR. The unique 'W' shaped louver profile has a shining specularly reflective surface. This louver design provides advanced features in rejecting summer solar radiation, but allowing winter solar radiation for daylighting purpose. This louver profile can vary in width from 50mm to 20mm depending on the application. The smaller 20mm version can be integrated into a standard insulating glass unit (IGU) as shown in Figure 2-9.



Figure 2-9 RetroLux® from RetroSOLAR image from: http://www.retrosolar.de/flash/ani rlux e.html

Despite the good features provided by this product, there are also some disadvantages compared to VisionControl® windows. First, like conventional venetian blinds, the louvers in this product are operated by cords. This limits this product from

being installed on an inclined facade surface (e.g. skylight applications) due to the contact between the metal louver and the glass. Second, when louvers are not integrated between two panes of glass, frequent maintenance is required to keep a clean reflector surface and only manual control is available.

OKASOLARTM from SCHOTT (<u>http://www.okalux.de</u>)

OKASOLAR[™] is another advanced fenestration product from Germany. This product has shining specular reflective louvers integrated between two panes of glass. As shown in Figure 2-10, this louver profile also provides good features such as the fact that solar radiation from a high incident angle will be reflected back to the exterior and solar radiation from a low incident angle will be able to penetrate for daylighting purpose. This product has an overall thickness of 1.5" including two panes of 1/4" glass. It can be used as a standard IGU for curtain wall constructions so it can be considered to have no extra installation cost. Since the louvers are sealed in the window cavity, maintenance is never needed for the louver surface.



Figure 2-10 OKASOLARTM from SCHOTT image from: <u>http://www.okalux.de/en/products/brands/okasolar/okasolar-w.html</u>

There are two main disadvantages of this product. First, the integrated louvers are not rotatable. Second, as can be seen from Figure 2-10, the view to the exterior is very limited due to the tilt angle and the thickness of the louver. This product is widely used in skylights and inclined curtain walls (shown on its official website).

LightlouverTM (<u>http://www.lightlouver.com</u>)

Lightlouver[™] is a patented light-redirecting louver system. It is an extra shading system mounted inside, directly adjacent to the glazing (as illustrated in Figure 2-11). The specularly reflective louvers are spaced closely so that all sunlight above a 5° altitude angle is redirected upward onto the ceiling of the daylit office. Figure 2-12 illustrates Lightlouver[™] installed on the top section of a three-section façade and how light is redirected towards the ceiling.

This product could not be integrated between two panes of glass and frequent maintenance is required to maintain a clean reflector surface. The louvers are placed close to each other so view to the exterior is not possible. Due to the fact that the louver can redirect direct sunlight with a high solar profile angle, excessive solar heat gain during summer is possible.



Figure 2-11 Lightlouver[™] - a daylighting louver system image from http://www.lightlouver.com/Info/Info.html



Figure 2-12 Lightlouver[™] installed on the top section of a three-section façade image from <u>http://www.lightlouver.com/Info/Info.html</u>

From the three reviewed products, it can be concluded that all advanced fenestration or shading products redirect part of the daylight towards the ceiling and to the back of the room. The light-redirection performance is highly dependent on the louver profile design. A good louver profile is effective in rejecting solar radiation from a high incident angle to protect the interior from excessive solar heat gain. Several products, but not all, are capable of integrating louver systems between two panes of glass. Cordoperated louver systems are not applicable for inclined façade surfaces or skylights due to direct contact between the glass and louvers. Some advanced products provide louvers in a fixed position which show better performance in redirecting daylight, but rotatable louver systems provide better control of transmitted daylight and the flexibility for occupants to choose what they need. It is also possible to close rotatable louvers for video presentations. View to the exterior is also an important factor when designing advanced fenestration products. It will enable the possibility of using the product on the viewing section of the facade to further reduce the use of conventional roller blinds. All the information extracted from this review is very important for the design of the new generation of VisionControl® window.

2.6 Three-section façade concept

To utilize the features offered by the new advanced fenestration products, a good façade design is essential. The three-section façade concept is widely used in commercial curtain walls with the top and middle sections covered by transparent window units, and a spandrel section covered by opaque panels. Tzempelikos et al. (2007) proposed a three-section multifunctional façade concept for a new institutional building. As shown in Figure 2-13, the proposed three-section façade utilizes advanced fenestration for the top daylighting section and conventional roller blind for the middle viewing section. On the spandrel section, photovoltaic panels are used for generating electricity. This façade design has great potential for providing daylight from the top section and good view to exterior while controlling excessive solar heat gain. Electricity generation is also a potential bonus feature from the opaque spandrel section if photovoltaic panels are integrated into it.



Figure 2-13 The proposed three-section multifunctional façade concept (Tzempelikos et al. 2007)

With the same three-section façade concept, Kapsis (2009) studied a bottom-up motorized shade and Robinson (2009) studied the potential of integrating semitransparent photovoltaics into the top section of the façade. Both studies concluded that with the help of separating the façade into top daylighting section and middle viewing section, better daylighting performance and more energy saving from the artificial lighting systems were achieved. More importantly, both studies confirmed that the threesection façade concept is ideal for studying new window/shading products and other new ideas.

2.7 Workplane illuminance prediction method

Integrated simulation of daylighting and artificial lighting plays a significant role in energy consumption, indoor environment and environmental impact as the fenestration system influences heat loss, solar gains and daylight penetration (Hviid et al. 2008). RADIANCE, DAYSIM, ESP-r and other commercial rendering software packages have the ability to simulate daylighting performance of a specific architectural design. However, to run these programs requires expert knowledge and large amounts of input data for even the simplest simulation. Rendering a complete scene is impractical at the early design stage when design parameters & information are scarce (Hviid et al. 2008). This calls for tools that are capable of rapid and dynamic calculation of the impact of fenestration and shading device on annual daylighting performance.

Robinson and Stone (2006) proposed a simplified indoor illuminance prediction algorithm that achieves good accuracy, in particular in the presence of reflecting neighboring buildings. However, this model does not account for the particular reflecting characteristics of venetian blinds.

Lehar and Glicksman (2007) designed a daylighting simulation tool to predict the distribution of daylight in an office room using a rapid calculation procedure. Results from this tool are compared to the software called RADIANCE, and are found to agree within 10% normalized error. This simulation tool uses data from location-specific weather files for its hourly lighting calculations and employed the radiosity method. This tool accounts for light reflecting off blind surfaces and each surface in the office is discretized into a mesh. The brightness of each mesh element is given arbitrarily an initial brightness and the algorithm iteratively refines that guess until equilibrium is reached. This innovative algorithm is able to reduce computation times from 15min to 3-5s.

Lindelof (2009) proposed a simplified daylight model that considers for a given position of the sun and for a given blind's settings, the indoor illuminances as a linear combination of outdoor horizontal global and diffuse irradiances. The model's inputs are previously recorded measurements of illuminance, blind settings and sun positions. This model has been validated on a RADIANCE model of an office with a south-facing window. This model is able to model indoor illumiances with a correlation R^2 = 0.98 by using hourly data at least one week old. The main advantage of this model is that it is a fast daylighting model suitable for an embedded daylight controller. A "toy" controller was created by the author and used to adjust the blinds so that the indoor illuminance was kept close to 500 lux.

Hviid et al. (2008) developed a simple building simulation tool for both integrated daylight and thermal analyses. This tool utilizes a coupled ray-tracing and radiosity methodology to derive the daylight levels for different sky conditions. It was programmed in Matlab® and uses an interface for inputs. However, this simulation tool

is validated only with RADIANCE simulation instead of experiments. Another limitation of the tool is that it is only valid for a single wall opening with one single window as shown in Figure 2-14. The ability to use this tool for advanced fenestration product or other types of façade design is unclear.



Figure 2-14 Example room model (Hviid et al. 2008)

Athienitis and Tzempelikos (2002) developed an integrated model based on CIE (Commission Internationale de l'Eclairage) clear and overcast sky formations for external illuminances and radiosity for internal illuminances. This approach produces a rapid calculation tool. However, simulation accuracy was limited by the quality of the input visible transmittance of the studied advanced fenestration.

A method to calculate the correlation between illuminance levels on interior surfaces and the daylight distribution was developed by Park and Athienitis (2003). This methodology enables the development of closed-loop control strategies that can be used to adjust the venetian blind tilt angle in order to increase the daylight contribution to the workplane.

2.8 Daylight performance metrics

Reinhart et al. (2006) pointed out that "one of the difficulties of pinpointing good daylighting may be that different professions concentrate on different aspects of daylighting". Due to the variation of dynamic shading devices and control strategies applied, there is a need for standard daylight performance metrics (Kapsis 2009).

Daylight Autonomy (DA) uses workplane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone (Reinhart et al. 2006). In 2001, Reinhart and Walkenhorst (2001) redefined daylight autonomy as "the percentage of the occupied times of the year when the minimum illuminance requirement (500 lux) at the sensor is met by daylight alone".

Useful Daylight Illuminance (UDI), proposed by Nabil and Mardaljevic in 2006, is a dynamic daylight performance measure that is also based on workplane illuminances (Nabil and Mardaljevic 2006). It aims to determine when daylight levels are 'useful' for the occupant and also to distinguish if the daylight is in the too dark range, comfort range or the too bright range. Based on the upper and lower thresholds of 2,000lux and 100lux, UDI results in three ranges show the percentages of the occupied times of the year when the UDI was achieved (100-2,000lux), fell-short (<100lux), or was excecd(>2,000lux) (Reinhart et al. 2006).

Chapter 3: MATHEMATICAL DAYLIGHTING MODEL OF THE THREE-SECTION FAÇADE CONCEPT WITH THE NEWLY DESIGNED VISIONCONTROL® WINDOW

3.1 Introduction

A mathematical daylighting model based on Perez all-weather sky model (Perez et al. 1993) and radiosity method was developed in MathCAD® version R14. This mathematical model was developed for rectangular office spaces with three-section curtain wall façades (shown in Figure 3-4), where VisionControl® windows are installed on both top and middle sections.

This model can predict the workplane illuminance distribution for different threesection façade designs with different façade orientations, VisionControl® windows with different louver surface finishes, room configurations (size, surface finishes etc) and control strategies. The radiosity method is considered valid for this mathematical model because the integrated louvers are controlled to block the direct sunlight at all times so that both sections of the façade become diffuse daylight sources. This mathematical model can be used to compare different three-section façade designs and investigate the annual daylighting performance of a defined façade design. This model builds on the work of Athienitis and Tzempelikos (2002) who developed a radiosity model for the earlier generation of VisionControl® window with one section façade.

Figure 3-1 shows the algorithm steps and the data flow of the mathematical model developed. Firstly, the user inputs the building location and façade configuration into the model. Then, the model calculates the solar angles which are used to describe the position of the sun relative to the façade surface. These solar angles are used as inputs for the

Perez all-weather sky model (Perez et al. 1993) and the control strategy applied on the three-section curtain wall façade.



Figure 3-1 Daylighting mathematical model and algorithm

The Perez all-weather sky model uses the weather data and solar angles as inputs to calculate the sky illuminance for daylighting simulations. It can accurately consider different weather conditions and calculate the total amount of daylight that is incident on a façade surface. Details about the Perez all-weather sky model can be found in Section 3.5.

A control strategy is implemented to rotate the louvers inside the VisionControl® window according to the position of the sun and prevent direct sunlight from entering the space, which usually causes glare in occupied spaces. Due to the feature provided by the combination of the VisionControl® window and the three-section façade concept, different control strategies can be applied individually to the top and middle sections of the façade. Occupants have the freedom to choose the control for what they need, such as maximum daylight, maximum view to the exterior or a dark environment for video presentations. A simplified control strategy was developed for this mathematical model and the details are described in Section 3.6.

The visible transmittance of VisionControl® window is considered as the key parameter in order to calculate the amount of daylight that is transmitted. However, the determination of the visible transmittance of VisionControl® window is a demanding task due to the fact that the VisionControl® window can be equipped with many different types of glazings and louvers with different surface finishes (Tzempelikos 2002). Moreover, the integrated rotatable louvers can be used to regulate the percentage of openness to the exterior which is another important factor. Therefore, to obtain visible transmittance value of the VisionControl® window for the mathematical model, an experiment was carried out. Details about this measurement are provided in Chapter 4.

In the last step, after the amount of transmitted visible daylight is determined, the interior workplane illuminances are calculated using radiosity method (Athienitis and Tzempelikos 2002). Therefore, inputs of room geometry and room surface optical properties are required. Radiosity method and detailed calculation steps can be found in Section 3.8.

3.1.1 The newly designed VisionControl® window

As a prerequisite to the mathematical daylighting model and an important part of this thesis, the development of the new generation of the VisionControl® window was started in October, 2007. This window product's 2.5" overall thickness limits it from many standard curtain wall constructions and other retrofit projects. It needs to be reduced before it can be widely used in the construction industry. After one and half years' development, a newly designed VisionControl® window with 1.5" overall thickness was successfully manufactured which provides the basic and important information for the development of the mathematical daylighting model.



Figure 3-2 The old 2.5" and the newly designed 1.5" VisionControl® windows

As shown in Figure 3-2, the overall thickness of the newly designed VisionControl® window is 1.5". Three different surface finishes are provided for the new louver and variable in colors. Figure 3-3 shows the three different surface finishes: from left to right, white painted (Duracon K-1250), clear anodized and bright-dip anodized. Table 3-1 summarizes the optical and physical properties of the three surface finishes. Detailed design considerations and strategies used during the development of the new VisionControl® window are provided in Appendix A.



Figure 3-3 Three different louver surface finishes

Table 3-1 Three different louv	er surface finishes/
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Surface finish	Type of reflection	Features	
White painted	Intermediate	UV*-stable	
		Various colors	
		UV-stable	
Bright-Dip anodized	Specular	Mirror-like smooth and shining	
		Natural color of aluminum	
		UV-stable	
Clear anodized	Diffuse	Rough surface (at the microscopic level)	
		Various colors	

*Ultraviolet

3.2 Inputs for the mathematical model

The following list summarizes the important inputs required for the mathematical model:

- Building location information (Latitude, Longitude)
- Three-section façade geometry and orientation
- Weather data input (irradiance data measured by a sun tracker)
- Control strategies for both top and middle sections of the façade
- Visible transmittance of VisionControl® window as a function of blind tilt angle and solar profile angle
- Room geometry
- Room surface reflectance

Figure 3-4 illustrates the required inputs regarding the geometry of the threesection façade and the dimension of the office room. This model requires user to input the height for each section of the three-section façade (H_{top} , H_{mid} and H_{sp}). In curtain wall façade, area covered by the structural aluminum mullions is not negligible and should be subtracted from the façade area to calculate glazing area (the light source area).



Figure 3-4 A typical office with three-section façade

3.3 Solar geometry calculation

The position of the sun is highly dependent on time, building location and façade orientation. Moreover, the control of the louver tilt angle is a function of sun position with the goal of blocking the direct sunlight.

Detailed calculation steps are well described in the MathCAD® program which is provided in Appendix C. Among all the calculated solar coordinates, the solar profile angle is considered the most important output and it is the driving parameter of the direct sunlight cut-off angle for the newly designed VisionControl® window. The program builds on work by the research team of Concordia University's Solar and Daylighting Laboratory, and in particular the work using the radiosity method (Athienitis and Tzempelikos 2002) (Kapsis 2009). In this thesis, it is extended to a three-section façade with the top and middle sections based on the newly designed VisionControl® window with independent control of the integrated louvers.

3.3.1 Solar profile angle

The control of the louver under clear sky conditions is highly dependent on the position of the sun relative to the façade surface. Before explaining the control strategy developed for the model, two important angles used in the control strategy need to be determined:

- Solar profile angle (λ)
- Direct sunlight cut-off angle ($\Omega_{cut-off}$)

As shown in Figure 3-5, the profile angle is defined as the projection of the solar altitude angle on the vertical plane perpendicular to the façade (O'Neill 2008). It can be calculated by the following equation:

$$\lambda = \tan^{-1}(\frac{\tan(\alpha)}{\cos(\gamma)})$$
 Eq. 3-1

Where α is the solar altitude and γ is the solar surface azimuth.



Figure 3-5 Profile angle of incident direct sunlight

3.4 Louver tilt angle and direct sunlight cut-off angle

3.4.1 Louver tilt angle

It is necessary to define the acceptable range for the louver tilt angle as the louver can be rotated in both clockwise and counter-clockwise directions. As illustrated in Figure 3-6, the louver tilt angle (β) is measured clockwise starting from the horizontal position with the exterior side and interior side specified clearly. The range of louver tilt angles between two fully closed positions is not -90° to 90°, but -85° to 85° due to the interlocking louver edge.



Interior

Figure 3-6 Define louver tilt angle

3.4.2 Direct sunlight cut-off angle

The direct sunlight cut-off angle is defined as the maximum tilt angle, counting from -85° (fully closed), to block all the direct sunlight from penetrating through the louvers. The determination of the direct sunlight cut-off angle requires the consideration of louver spacing, louver thickness, the interlocking louver edges and the variation of solar profile angle. With the 3D design software Autodesk® Inventor®, a graphical simulation was conducted to determine the relation between the direct sunlight cut-off angle and the solar profile angle. As displayed in Figure 3-7, series of parallel lines were generated to simulate the direct sunlight with a specified profile angle (35° shown in Figure 3-7). Then the corresponding cut-off angle can be determined by rotating the louver until no light can penetrate through the space between two adjacent louvers. As shown in Figure 3-7, the two lines are obstructed by louvers, which imply that no light can penetrate through the window.



Figure 3-7 Determination of direct sunlight cut-off angle with software Autodesk Inventor®

This simulation was repeated for varying solar profile angles at an interval of 5° from 0° to 90° . All results are plotted in Figure 3-8, a linear relation between the direct sunlight cut-off angle and the solar profile angle was found to fit the data well. The following equation that can be used for the control strategy to block direct sunlight:

$$\Omega_{\rm cut-off} = 1.8299 * \lambda - 67.343$$
 Eq. 3-2

where $\Omega_{cut-off}$ is the direct sunlight cut-off angle and λ is the solar profile angle.



Figure 3-8 Filtted linear relationship for direct sunlight cut-off angle as a function of solar profile angle

3.5 Perez all-weather sky model

Perez all-weather sky model (Perez et al. 1993) has been developed in the early nineties by Richard Perez. This model requires date, time, direct and diffuse irradiance values to calculate the sky luminous distribution for a given sky condition. It is based on a large data base of sky conditions and uses "bins" for the sky clearness from 1 to 8 (Perez et al. 1990).

Perez all-weather sky model consists of two independent models (Reinhart 2006):

• The Perez luminous efficacy model calculates the mean luminous efficacy of the diffuse and the direct sunlight for a considered sky condition. Input parameters are the solar zenith angle, solar altitude, direct and diffuse illuminance as well as the atmospheric water content.

• The Perez sky luminous distribution model calculates the sky luminous distribution based on date, time, direct and diffuse illuminance. The model comprises five parameters which influence the darkening or brightening of the horizon, the luminance gradient near the horizon, the relative intensity of the circumsolar region, the width of the circumsolar region and the relative intensity of light back-scattered from the earth's surface (Reinhart 2006).

3.6 Control strategy for the three-section façade

The integrated rotatable louver inside the VisionControl® window is considered as one of the unique features provided by this advanced fenestration product. It allows occupants to change the position of the louver to adjust the amount of transmitted daylight or the percentage of view through the window. When combined VisionControl® windows are integrated with three-section façade concept, the top and middle section of the façade can be controlled independently for different purposes.

3.6.1 The "glare-free" range for louver tile angle

An important parameter used in the development of the control strategy used in this mathematical model is called "glare-free" range for louver tilt angle. As illustrated in Figure 3-9, for a specific solar profile angle, louvers can be rotated freely from -85° to the cut-off angle without any direct sunlight penetrating the window. The range of louver tilt angle from -85° to the direct sunlight cut-off angle is defined as the "glare-free" range. This range is the determining parameter for the development of the control strategy used in this model.



Figure 3-9 The "glare-free" range a given sun position (solar profile angle)

3.6.2 Control strategy

The control strategy developed for this mathematical model controls the top and middle section independently, utilizing the concept of the three-section façade that different section can be controlled for different purposes. For that reason, the louvers on both top and middle sections are controlled to block direct sunlight from entering the interior at all times, and also for the following purposes:

- Top section for the maximum visible daylight transmittance
- Middle section for the maximum view to exterior

Figure 3-10 shows the detailed steps of the control strategy used in the mathematical model. The inputs of the control strategy are the calculated solar profile

angle and the amount of daylight incident on the exterior façade surface. The existence of clear or overcast sky conditions is determined based on the beam irradiance from the sun:

Sky conditions = Clear if
$$I_{beam} > 100 \frac{\text{watt}}{\text{m}^2}$$

The use of beam irradiance is valid only when TMY2 (Typical Meteorological Year) weather data is used or a sun-tracker is present. The existence of clear or overcast sky condition could also be determined based on the total exterior façade solar irradiance level. In this case, a value of 250 watt/m² could be used to mark the boundary between clear and overcast sky conditions.



Figure 3-10 Flow chart of the control strategy

3.7 Visible transmittance of the newly designed VisionControl® window

An important output from the control strategy is the range of louver tilt angles that can be applied to the top and middle sections of the façade. The visible transmittance of the VisionControl® window is considered as the key parameter in order to calculate the amount of daylight that is transmitted through the façade, and it is highly dependent on the louver tilt angle (Tzempelikos 2002). All these important factors should be considered in the determination of the visible transmittance of VisionControl® window.

An experiment was carried out to measure the visible transmittance of VisionControl® window in order to obtain visible transmittance value for the mathematical model. In this experiment, a custom-built testing device was designed and constructed. Detailed experiment setup, steps and results are described in Chapter 4.

3.8 Radiosity method

After the total amount of daylight transmitted through the façade has been determined, the radiosity method is used in this mathematical model to calculate the final illuminance levels on the workplane. Radiosity method was first developed in 1950s in the engineering field of heat transfer. It was later refined specifically for application to the problem of rendering computer graphics in 1984 by researchers at Cornell University (Goral et al. 1984). Radiosity method could also be used to calculate the luminous flux transfer between surfaces for lighting analysis.

The basic luminous flux transfer equation (Eq. 3-4) in a diffuse enclosure is:

$$M_i = M_{i,o} + \rho_i \sum M_j F_{ij} \qquad \qquad Eq. 3-4$$

Where:

 M_i = final luminous exitance of surface i

 $M_{i,o}$ = initial luminous exitance of surface i

 ρ_i = diffuse reflectance of surface i

 M_i = final luminous exitance of surface j

 F_{ij} = view factor of surface j relative to surface i

3.8.1 View factor between surfaces

View factor from surface A to surface B is defined as the proportion of luminous flux (radiation) that is emitted by surface A and received by surface B. The fundamental expression for a view factor between two isothermal surfaces considered as blackbodies with diffuse emittances is:

$$F_{1\to 2} = \frac{1}{\pi A_1} \int_{A_1} \int_{A_2} \frac{\cos(g_1) * \cos(g_2)}{r^2} dA_2 dA_1$$
 Eq. 3-5

Where A_1 and A_2 are the areas of surface 1 and 2, g_1 and g_2 are the angles between the unit normals n_1 and n_2 to surface differential elements dA_1 and dA_2 (Walton 2002).



Figure 3-11 Geometry and Nomenclature for Eq. 3-5



Figure 3-12 Unfolded room surfaces

To simplify the identification of each surface during the view factor calculation between interior surfaces, all room surfaces are unfolded and a number is given to each surface, as illustrated in Figure 3-12. The façade is divided into three surfaces because the top and middle sections of the façade are considered as different light source regions. After all view factors between all interior surfaces have been calculated, results are summarized in matrix **F** as follows:

$$\mathbf{F} = \begin{pmatrix} F_{22} & F_{23} & \cdots & F_{29} \\ F_{32} & F_{33} & \cdots & F_{39} \\ \vdots & \cdots & \ddots & \vdots \\ F_{82} & F_{83} & \cdots & F_{89} \\ F_{92} & F_{93} & \cdots & F_{99} \end{pmatrix}$$
 Eq. 3-6

3.9 Calculation of workplane illuminance

Luminous exitance is defined as the density of luminous flux leaving a surface (Murdoch 2003). After the visible transmittances for top and middle sections are determined, the initial luminous exitance of the interior surfaces of top and middle sections (light source surfaces) can be calculated by:

$$M_{top} = E * \tau_{top} \qquad \qquad Eq. 3-7$$

$$M_{mid} = E * \tau_{mid} \qquad \qquad Eq. 3-8$$

where E is the illuminance on the exterior façade surface and τ_{top} and τ_{mid} are visible transmittances for top and middle sections respectively.

The initial luminous exitances of all eight room interior surfaces are summarized in matrix M_0 with the following format:

$$\mathbf{M_{o}} = \begin{pmatrix} M_{top} \\ M_{mid} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$
 Eq. 3-9

The reflectances for all eight room interior surfaces written in matrix format:

$$\boldsymbol{\rho} = \begin{pmatrix} \rho_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \rho_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \rho_7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \rho_8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \rho_9 \end{pmatrix}$$
Eq. 3-10

The final luminous exitances of all interior surfaces M_{final} after infinite interreflections are calculated by:

$$M_{final} = (I - \rho * F)^{-1} * M_o$$
 Eq. 3-11

where I is a 8*8 identity matrix of 0's with 1's along the diagonal.

Workplane illuminances are calculated for five measurement points located along the center line of the room, so that they can also be compared with measured data in the validation experiment described in Chapter 5. Configuration factors are required in the calculation of workplane illuminance. Configuration factor $c_{a\rightarrow b}$ is defined as the ratio of the illuminance at surface 'a' produced by the flux received directly from surface 'b' due to the luminous exitance of surface 'b' (Murdoch 2003). Configuration factors between each sensor point and each room surface needs to be calculated and summarized in matrix format:

 $\mathbf{C}_{\mathbf{i}} = \begin{pmatrix} \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}2} & \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}3} & \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}4} & \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}5} & \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}6} & \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}7} & \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}8} & \mathbf{c}_{\mathbf{i} \rightarrow \mathbf{s}9} \end{pmatrix} \quad \text{Eq. 3-12}$

Where, $c_{i\rightarrow s2}$ is the configuration factor between the measurement point i (ranging from i=1 to i=5) and Surface 2 (the top section of the façade).



Figure 3-13 Workplane illuminances are calculated at five points alone the center line of the room as shown

The final workplane illuminance is calculated at five points along the center line of the room, as shown in Figure 3-13, by multiplying the configuration factors with the final luminous exitances of all room surfaces.

3.10 Assumptions used in the mathematical model

The basic assumption in the radiosity method is that all interior room surfaces are assumed to be perfectly diffuse. Conventional interior dry wall finish and ceiling tiles normally have diffuse surfaces that are very close to the ideal perfectly diffuse surface. Another important assumption is that any daylight transmitted through the VisionControl® window is perfectly diffuse light source. This assumption seems invalid

for clear day conditions when direct sunlight is incident on the façade surface. However, due to the integrated rotatable aluminum louvers and the control strategy that is developed with this mathematical model, direct sunlight is always blocked by the aluminum louvers and diffused before entering the room. The validation experiment explained in Chapter 5 confirms that this assumption is valid and workplane illuminance can be calculated using this mathematical model with reasonable accuracy.

The control strategy developed with this mathematical model assumes that no occupant override is allowed. Top section of the façade is always controlled for maximum daylight transmittance and the middle section is always controlled for the maximum view to the exterior. The intensity of direct irradiance is used to separate clear sky conditions and overcast sky conditions. When direct solar irradiance is higher than 100 watt/m², the control strategy rotates the louvers to block direct sunlight, then visible effective transmittances obtained under clear sky conditions are used for future calculation (for more detail, please see Chapter 4). When direct irradiance is lower than 100 watt/m², the control strategy fully opens both top and middle sections and then visible transmittances obtained under overcast sky conditions are used for future calculation.

Chapter 4: MEASUREMENT OF VISIBLE TRANSMITTANCE OF THE NEWLY DESIGNED VISIONCONTROL® WINDOW

4.1 Introduction

The effective visible transmittance of the newly designed VisionControl® is one of the most important inputs in order to develop an accurate mathematical model to predict the workplane illuminance distribution for the three-section curtain wall façade. This chapter explains a simplified method of measuring the visible transmittance of the window with the consideration of several important aspects such as different solar profile angles, louver tilt angles and louver surface finishes. In this experiment, a custom-built testing device was designed and constructed.

Generally, the visible transmittance of fenestration products is calculated by:

Visible Transmittance
$$(VT) = G_{tran}/G_{in}$$
 Eq. 4-1

where G_{tran} is the transmitted visible light and G_{in} is the incident visible light.

However, the visible transmittance of the VisionControl® window is affected by many aspects that can be categorized as follows. Firstly, materials used in the window, such as types of glazing and louver surface finish, have direct impact on the visible transmittance. Secondly, the visible transmittance also varies with the properties of the incident light which are defined by the sky conditions. In this experiment, the effective transmittance for total solar radiation is used, but better accuracy would be obtained if separate diffuse and beam transmittances were used. However, this requires a special testing device to separate the direct and diffuse daylight during the measurement, which increases complexity. Thirdly, the integrated rotatable aluminum louvers allow the visible transmittance of the window to be adjusted by changing the louver tilt angle.

4.2 Optical properties of glazings

The visible transmittance of VisionControl® windows are highly dependent on the type of glazing used. Coatings are increasingly becoming the focus of glass performance related research because they are considered an effective method of improving the thermal and lighting performance. With the help of new technologies in glass coatings, solar control glasses can filter the solar radiation in the non-visible range, but allow the visible light to penetrate. This type of glass normally has a high visible transmittance but a low total transmittance. The visible transmittance of glass is also highly dependent on the coatings that are used on its surfaces. Solar control glass and low-emissivity glass are the two main types of advanced glasses widely used in building constructions.

Low-emissivity (Low-E) glass has a thin coating, often of metal, that reflects longwave radiation back into a building to achieve much lower heat loss than an ordinary clear glass. Additionally, different types of low-emissivity glass allow different amounts of passive solar heat gain which helps reduce heating requirements and costs, especially in cold climates (Pilkington Group 2009).

Both solar control and low-emissivity coatings maintain high visible transmittance while controlling radiation in the non-visible range. An insulating glass unit (IGU) is able to use solar control glass as the exterior pane for the best control of excessive solar heat gain and low-emissivity glass as the interior pane to reduce heat loss in winter (shown in Figure 4-1).



Figure 4-1 Insulated glass Unit incorporating coated solar control glass or Low-e glass (Pilkington Group 2009)

4.3 Optical properties of louver surface finishes

As mentioned in Section 3.1.1, there are three different louver surface finishes provided with the newly designed VisionControl® window. The three different surface finishes provide different types of reflections, covering diffuse, intermediate and specular reflections. Visible reflectances of these three surface finishes were measured by Gigaherz-Optik® LCRT2000 reflectrometer with measured results listed in Table 4-1. Figure 4-2 illustrates how the light reflection from a surface changes with the roughness of the surface.

Sample No.	Surface finish type	Type of reflection	Visible reflectance
1	White paint	Intermediate	73.2%
2	Clear anodized	Specular	65.2%
3	Bright-dip anodized	Diffuse	68.9%

Table 4-1 Total hemispherical reflectance of three louver samples with different surface finishes



Figure 4-2 Diffuse, intermediate and specular reflections Image from: <u>http://micro.magnet.fsu.edu/primer/java/reflection/specular/index.html</u>

4.4 Sky conditions

The sun is the original source of any type of daylight. Due to the water vapor and dust contained in the atmosphere, direct sunlight is scattered by these small particles and the sky dome becomes the secondary source of daylight. The variation of clouds in the sky causes different sky conditions such as clear, intermediate and overcast. These sky conditions influence the visible transmittance measurement of the VisionControl® window for the following reasons:

- Under clear sky conditions, the sun is the main source of daylight due to the presence of direct sunlight and the sky dome (mainly in blue) is the secondary source of daylight.
- Under overcast sky conditions, the sun is blocked by clouds and the sky dome is the only source of diffused daylight.
- Under intermediate sky conditions, the sun is blocked by the clouds in the sky from time to time and the sky is partial white (the clouds) and partial blue (area between clouds)

Daylight coming directly from the sun is highly directional but daylight coming from the sky dome is diffuse. When direct sunlight is incident on the window surface, the integrated louvers can redirect part of the direct sunlight into the interior. However, this function is highly dependent on the louver surface finish and the louver tilt angle.

4.5 Experiment location

The experiment was undertaken in an open area in Longueuil, Quebec. There is no neighboring building more than two stories high or any other obstruction to direct sunlight (as shown in Figure 4-3).



Figure 4-3 The open backyard

4.6 Custom-built testing device

A special custom-built testing device was designed and constructed in order to simplify the measurement of visible transmittance of VisionControl® window and to avoid purchasing an expensive goniophotometer. In the design of the testing device, several important factors were considered, such as different direct sunlight profile angles and louver tilt angles. A schematic of the custom-built testing device is shown in Figure 4-4.

As shown in the top left photo in Figure 4-5, the custom-built testing device is made of an aluminum window frame with the tested sample of VisionControl® window unit installed in it. This window frame was constructed with curtain wall mullions and pressure plates which makes it very convenient to change the tested window sample. Top right photo shows the detail of the two joints for tilting the testing device. The reason to design such joints is to allow tilting the testing device for different solar profile angles during measurements. By tilting the testing device, any solar profile angle can be achieved, greatly reducing the total amount of time required for the experiment.


Figure 4-4 Schematic of the custom-built testing device

Under the installed VisionControl® window, a gypsum board was attached to simulate the ground and was painted grey with a reflectance of 25% (installed perpendicular to the window surface). The whole testing device was installed on a buggy,

which carries the data acquisition system and also allows it to be rotated and moved easily.

The bottom left photo in Figure 4-5 shows the cavity behind the VisionControl® window. All interior surfaces of the cavity were painted black to make sure no light could be reflected from behind the sensor which would affect the accuracy of the experiment. There were ten photometric sensors used, installed behind the window unit, supported by an aluminum strip shown in the photo. The spacing of sensors was carefully considered and the details are described in Section 4.7.1.



Top left: the custom-built testing device; Top right: the two joints for tilting the testing device. Bottom left; the detail of the cavity behind the VisionControl® unit and the installation of 10 sensors behind the window unit; Bottom right: back of the window is closed by an aluminum panel with a white crank handle operating the louver inside the VisionControl® window.

Figure 4-5 Photos of the custom-built testing device

The last photo in Figure 4-5 shows the rear side of the custom-built testing device with the back cover panel installed. The inside surface of the back panel was also painted black to ensure no light could be reflected and affect the experiment's accuracy. On the right side of the panel, white crank handle is used to rotate the louvers inside the VisionControl® window during the experiment.

4.7 Sensor and sensor layout

In this experiment, a total of 12 Li-Cor 210 Photometric sensors (as shown in Figure 4-6) were installed. These photometric sensors have a spectral response from 380nm to 700nm and are pre-calibrated against a standard lamp using 683 lumens per watt as the value of spectral luminous efficacy at a wavelength of 555nm (LI-COR Biosciences 2008). Other important specifications such as accuracy and stability are listed in Table 4-3.

Table 4-2 Important specifications about Li-Cor 210 Photometric sensor (LI-COR Biosciences 2008)

Absolute Calibration:	$\pm 5\%$ traceable to NIST*	
Linearity	Maximum deviation of 1% up to 100klux	
Stability	<=2% change over1 year period	
Temperature Dependence	±0.15% per °C maximum	
Cosine Correction	Cosine corrected up to 80° angle of	
	incident	

*National Institute of Standard and Technology (NIST)



Figure 4-6 Li-Cor 210 Photometric sensor (LI-COR Biosciences 2008)

4.7.1 Sensor layout

As shown in Figure 4-7, two sensors are installed one on each side of the window to measure the illuminance on the exterior window surface, and ten sensors are installed behind the window unit to measure the transmitted illuminance. Special consideration was given to the ten interior sensors as discussed in Section 2.6.1. As illustrated in Figure 4-8, ten measurement points are considered sufficient to measure the illuminance transmitted between two adjacent louvers with accurate results. However, it was impossible to put ten sensors between two adjacent louvers (21.2 mm) due to the size of the photometric sensor which is 25.4 mm. For this reason, the spacing between two sensors was selected so as to cover the different locations between two louvers and to provide an accurate average illuminance measurement (details are shown in Figure 4-8).







Figure 4-8 Interior sensor layout to approximate 10 measurement points between two adjacent louvers

4.8 Tested VisionControl® window samples

As mentioned in Section 4.2, the type of glazing and louver surface finish used in the tested VisionControl® window has great influence on this experiment. Two VisionControl® samples with different types of louvers were manufactured and tested in this experiment. As shown in Figure 4-9, the first sample used white painted louvers and the other sample used bright-dip anodized louvers. Both windows used clear tempered glazing with a transmittance of 88%. The two samples are both 30" by 30" which is large enough to eliminate the effect of the window frame on the interior sensors.



Figure 4-9 Two VisionControl® samples used in this experiment

4.9 Experimental procedure

The experiment was carried out in the following steps:

- Before starting the measurement, a flat ground surface was located in the backyard to place the testing device to make sure the testing device was level during the measurements.
- 2. Rotate the testing device about the vertical axis so that the window faces the sun which provides a 0° surface azimuth angle.

- Lock the wheels of the buggy to make sure the testing device does not move during measurements.
- 4. Measure the solar profile angle; tilt the testing device to make the solar profile angle needed for each measurement. For example, 0° solar profile angle means the direct sunlight is perpendicular to the window surface and this angle can be achieved by tilting the testing device.
- 5. Once the tilt angle is found, tighten the screws at the joint to make sure the tilt angle does not change during measurements.
- 6. Rotate the louvers, and take a measurement for each louver tilt angle at each interval of 15°.
- 7. The visible transmittance for each measurement is calculated by taking the average illuminance measured by the ten interior sensors and dividing by the average illuminance measured by the two exterior sensors:

$$VT = \frac{Average value of trasmitted illuminance}{Average value of exterior surface illuminance} * 100\% Eq. 4-2$$

8. Repeat step 4 to 7 for another solar profile angle.

4.10 Experimental results

4.10.1 White painted louvers

Both line type figure (Figure 4-10) and contour-type figure (Figure 4-11) are used to illustrate the visible transmittance results measured for the VisionControl® window with white painted louvers under clear sky conditions.

In Figure 4-10, each line shows the visible transmittance results measured under a specific solar profile angle for different louver tilt angles. For all measured solar profile angles, the visible transmittance reaches the maximum value when the louver tilt angle is equal to the solar profile angle (louvers are operated parallel to the direct sun light), except 90° solar profile angle. This scenario matches the physical definition of visible transmittance that when louvers are operated parallel to the direct sunlight, more daylight can penetrate through the window. For 90° solar profile angle, the maximum visible transmittance occurs at 15° louver tilt angle. This is because, at a solar profile angle of 90° the sunlight is parallel to the window so that no direct sunlight can be received by the window surface but only diffused daylight from the sky dome. Under this situation, the more open the louver the higher the visible transmittance. The maximum value appears at 15° instead of 0° (fully open position) because under 15° louver tilt angle, more light can be redirected from the sky dome into the interior.

As illustrated in Figure 4-10, for the VisionControl® window with white painted louver, the maximum visible transmittance is at 15° solar profile angle and 15° louver tilt angle with a value of 65%. The reason is that at 15° solar profile angle, the sun is very low and more daylight can be reflected by the ground surface and reach the window surface. The results are plotted again in contour-type plot (as shown in Figure 4-11).

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Lighter colors are used for higher visible transmittance and darker colors for lower visible transmittance. A line is added in the figure to mark the position when the louvers are operated parallel to the direct sunlight (louver tilt angle = solar profile angle). It is clear that the lighter color region follows the line.

Figure 4-12 shows the visible transmittance results measured under overcast sky conditions. For overcast sky conditions, no direct sunlight is present and daylight received by the window surface is non-directional diffuse. The maximum visible transmittance values appear at an angle between 15° and 30° louver tilt angle instead of 0° (fully open position). The reason is that at 15° or 30° louver tilt angle, the louvers open toward the sky dome so that more daylight could be redirected into the interior. Under overcast sky conditions, the maximum visible transmittance is 40%.



Figure 4-10 Visible transmittance for VisionControl® window with white painted louver (clear day) (Line figure)



Figure 4-11 Visible transmittance for VisionControl® window with white painted louver (clear day) (Contour figure)



Figure 4-12 Visible transmittance for VisionControl® window with white painted louver (overcast day)

4.10.2 Bright-dip anodized louvers

Another VisionControl® window sample unit with bright-dip anodized louvers was tested. The results are plotted in Figure 4-13 and Figure 4-14.

Comparing to Figure 4-10, the results shown in Figure 4-13 are more randomly distributed. The maximum visible transmittance also appears at 15° solar profile angle and 15° louver tilt angle with a slightly higher value of 70%.



Figure 4-13 Visible transmittance for VisionControl® window with bright-dip anodized louvers (clear day) (Line figure)



Figure 4-14 Visible transmittance for VisionControl® window with bright-dip anodized louvers (clear day) (Contour figure)

From Figure 4-14, it is noticed that the light colored area also follows the line that indicates the position when louvers are operated parallel to the direct sunlight. Comparing Figure 4-14 with Figure 4-12, the light colored area in Figure 4-14 is larger, which means that the specular reflective louver surface finish provides higher visible transmittance for a wider range of solar profile and louver tilt angles. The reason for this phenomenon is that specular reflective surface finish is beneficial for maintaining the intensity of direct sunlight after multiple inter-reflections between louvers.

For overcast sky conditions, Figure 4-15 shows very similar results as Figure 4-12. The maximum visible transmittance also appears around 15° louver tilt angle but with a slightly higher value of 47%.





4.10.3 Direct and diffuse transmittances

Better accuracy would be obtained if separate transmittance values for direct and diffuse daylight were used rather than a combined effective transmittance value. The transmittance value obtained under overcast sky condition could be considered as diffuse transmittance $\tau_{diffuse}$ due to the lack of direct sunlight. Under clear sky conditions, both direct sunlight and diffuse sunlight are present. A simple calculation can be used to verify that the difference between the direct transmittance and the measured total visible transmittance under clear sky conditions is not significant. The following data obtained from the experiment is used in this calculation:

For clear sky conditions, 45° solar profile angle and 45° louver tilt angle data is used.		
Total exterior façade illuminance	80106 lux	
Exterior façade illuminance due to diffuse daylight (assumption)	10000 lux	
Exterior façade illuminance due to direct sunlight	70106 lux	
Total transmitted daylight	30128 lux	
Direct transmittance (τ_{direct})	To be determined	

Table 4-3 Data used for direct transmittance estimation

For overcast sky conditions, 45° louver tilt angle data is used (white painted louver).		
Diffuse transmittance ($\tau_{diffuse}$ obtained from Figure 4-12 with	33%	
45° louver tilt angle)		

With the following equation, and $\tau_{\text{diffuse}} = 33\%$,

70106 lux *
$$\tau_{direct}$$
 + 10000 lux * $\tau_{diffuse}$ = 30128 lux Eq 4-3

the calculated direct transmittance – τ_{direct} = 38%. From Figure 4-10 with 45° solar profile angle and 45° louver tilt angle, the total visible transmittance is 37%. The calculated direct transmittance τ_{direct} is close to the total visible transmittance measured under clear sky conditions. This comparison confirmed that visible transmittance obtained under clear sky conditions is close to the direct transmittance due to the fact that over 80% of the visible light is direct sunlight.

Chapter 5: MODEL VERIFICATION AND EXPERIMENTAL RESULTS

5.1 Introduction

A sample unit of the newly design VisionControl® window was used in this experiment. In order to validate the mathematical model, a typical three-section curtain wall façade with VisionControl® windows covering both top and middle sections, was studied.

5.2 Experimental setup

This experiment was carried out in a test hut located on the roof of a three-story building located in Concordia University, downtown Montreal. As illustrated in Figure 5-1, a 1:3 scale office model was constructed with gypsum board (interior board), plywood (to support gypsum board) and aluminum structural frames. This room model is used to simulate a typical rectangular office which is 3m high, 3m wide and 6m deep.



Figure 5-1 The 1:3 scale office model inside a test hut

The façade of the room model is covered by the newly designed VisionControl® window which is used to simulate the three-section curtain wall façade. As shown in Figure 5-2, the façade surface of the room model extends through a south-facing opening of the test hut, but the rest of the model is inside the test hut.



Figure 5-2 Exterior view of the test hut with the office model extended out of its south-facing opening

Figure 5-3 shows the VisionControl® window unit which is specially designed to simulate the three-section curtain wall façade. The louvers on the top part and bottom part can be manually controlled independently by two thumbwheels located on each side of the unit. Bright-dip anodized louvers were used on both top and middle sections of the façade.

Inside the office model, all interior surfaces of the model were finished with typical off-white painted drywall, including the spandrel section of the façade (as shown in Figure 5-4).



Figure 5-3 Close-up view of the newly designed VisionControl® window prototype



Figure 5-4 Interior sensor layout and data acquisition system

A total of 11 Li-Cor 210 Photometric sensors were installed for this experiment. Two sensors were placed outside the test hut to measure the global horizontal illuminance (located on the top of the test hut and orientated horizontally) and the exterior façade surface illuminance (located on the exterior surface of the VisionControl® window and orientated vertically). Nine sensors were installed inside the room model and supported at the workplane height (762mm above the floor). As shown in Figure 5-4, these nine sensors were positioned in a 3 by 3 grid. The front, middle and back rows of were placed at 1m, 3m and 5m from façade respectively. An Agilent 34970A data acquisition system was used to capture the readings from all eleven sensors and transfer them to a PC with Agilent VEE Pro 7.0 installed for data storage and analysis.

5.3 Small scale model for daylighting study

Thanachareonkit and Scartezzini (2005) conducted a daylighting study of a building with both a full scale test and its 1:10 scale model. This study concluded that scale model assessments generally overestimate the building's daylighting performance. The discrepancy between buildings and scale models is caused by several sources of experimental error, such as modeling of building details, imperfect replication of surface reflectances and glazing transmittances.

Although application of scale models is always questioned because they may lead to over-estimation in illuminance levels, they are employed in this study because they allow the use of small size three-section façade with the newly designed VisionControl® window. Piccolo and Pennisi (2009) also pointed out that "the small scale model allows using a reduced number of sensors and instruments thus saving times and costs, still remaining most of the physical behavior of light".

5.4 Weather data

The weather data used to validate the model should be obtained from the same location as the experiment. However, no detailed direct and diffuse solar irradiance data is available from Montreal weather stations. The closest available solar irradiance data was provided by a solar tracker installed at Natural Resource of Canada (NRCan), Varennes, Quebec, which is 15 km away from the experimental setup in Montreal. This location difference introduced some error to the model validation and the details are explained later in the next section.

The weather data provided from Varennes includes hourly ambient temperature, beam normal irradiance, diffuse horizontal illuminance and global horizontal illuminance. The dew point temperature, another required input to the Perez all-weather model, was obtained from Environment Canada's online weather data base (Environment Canada 2009).

5.5 Model validation

Experiments were conducted during the summer and continuous experimental results were observed from May 1st 2009 to July 1st 2009. During this time, various sky conditions occurred and the louvers on both top and middle sections of the three-section façade were kept at fully open position (horizontal). Table 5-1 lists three days with representative sky conditions (overcast, intermediate and clear) which were selected for this validation. Figure 5-5 illustrates three example photos for overcast, intermediate and clear sky conditions.

Case number	Date	Sky conditions
1	June 9	Overcast
2	May 16	Intermediate
3	May 13	Clear

Table 5-1 Three representative days used for model validation



Figure 5-5 Example photos for overcast (top left), intermediate (top right) and clear (bottom) sky conditions Images from: <u>http://www.tutorialsforblender3d.com/Textures/Skys/Sky_Dome_2.html</u>

The validation process can be summarized in three steps:

- Compare Global horizontal irradiance data from Varennes with the measured Global horizontal illuminance from Montreal to see if weather conditions are similar in the two locations. If large weather data deviations were found, corrections were made before any further comparison.
- 2. Compare the exterior façade vertical illuminance calculated by the Perez model with the measured value obtained from experiment.
- 3. Interior workplane illuminance distribution is compared at three points along the center line of the room. The three points are located at 1m, 3m and 5m from the façade and their illuminance levels generally represent the front, middle and the back of the room. In the calculation of relative error for each data unit, the experimental data was assumed as the "true" data. It is the best assumption that can be made for the error discussion due to the fact that weather condition is not repeatable.

5.5.1 Case 1: June 9th, 2009 (Overcast sky conditions)

Figure B-1 in Appendix B shows the hourly weather condition description obtained from Environment Canada, for Montreal (Pierre Elliott Trudeau airport weather station) on June 9th, 2009. As shown in the last column, June 9th, 2009 was an ideal overcast day due to the rain and foggy conditions.

Step 1: Compare sky conditions in Montreal and Varennes

This step verifies that on June 9th, 2009, Montreal and Varennes had similar weather conditions so it could be chosen as a representative day for model validation. However, due to the lack of irradiance data from Montreal weather stations, the global

horizontal illuminance data was used to compare the weather difference between Montreal and Varennes. As shown in Figure 5-6, the primary vertical axis is irradiance and the secondary vertical axis is illuminance. The scale of the second axis is adjusted to overlap the two curves in the figure as much as possible for the comparison. As can be seen from the top figure of Figure 5-6, large deviation were found for data points at 2pm and 3pm – Montreal was much brighter than Varennes. Without proper data correction, these two data points would cause very high errors. In order to minimize the error caused by the differences in weather between Montreal and Varennes, these two data points have been corrected (the Varennes data was fit to the Montreal data). The corrected weather data is illustrated in the lower figure in Figure 5-6. The maximum global horizontal illuminance appeared at 12pm with a value of 7000lux. It also confirms that June 9th, 2009 was a typical overcast day.



Figure 5-6 Measured global irradiance from Varennes compared to measured exterior horizontal illuminance from Montreal (June 9th 2009, overcast day) Two data points with large weather deviations have been corrected

Step 2: Compare model-calculated exterior façade vertical illuminance to measured

Figure 5-7 illustrates the comparison between the model-calculated and measured exterior façade vertical illuminance. The results match well throughout the entire day. This step confirms that the Perez all-weather sky model is accurate in calculating the illuminance incident on a façade surface with the irradiance weather data input. This step also works as a check point to validate that the same amount of daylight that is incident on the exterior façade surface in both simulation and experiment. This check is important before any future calculation of the transmitted daylight and the interior workplane illuminance distribution in step 3.



Figure 5-7 Model-calculated exterior façade vertical illuminance compared to measured (June 9th 2009, overcast day)

Step 3: Compare illuminance level at three workplane measurement points

Comparison between the model-calculated and measured workplane illuminance distribution was carried out to examine the accuracy of the mathematical model developed. Three workplane points along the center line of the room are chosen for this comparison. The three points are located at 1m, 3m and 5m from the façade (room total depth is 6m) and their illuminance levels generally represent the brightness of the front, middle and the back parts of the room.

The comparison between model-calculated and measured workplane values is illustrated in Figure 5-8, Figure 5-9 and Figure 5-10. Relative error is calculated for each data point and used to show the accuracy of the mathematical model. For all three figures, relative errors are within $\pm 25\%$. It can be seen that the back of the room (5m from the façade) has higher error than the front or middle measurement points. This is because, at the back of the room, the absolute illuminance value is lowest. A small difference in illuminance can lead to a large relative error if the absolute illuminance is also small.



Figure 5-8 Model-calculated workplane illuminance at 1m from façade compared to measured (June 9th 2009, overcast day)



Figure 5-9 Model-calculated workplane illuminance at 3m from façade compared to measured (June 9th 2009, overcast day)



Figure 5-10 Model-calculated workplane illuminance at 5m from façade compared to measured (June 9th 2009, overcast day)

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5.5.2 Case 2: May 16th, 2009 (Intermediate sky conditions)

The occurrence of completely clear or overcast days is low compared to intermediate days which have mixed partially clear and partially overcast sky conditions.

Step 1: Compare sky conditions in Montreal and Varennes

As shown in Figure 5-11, May 16^{th} 2009 is an ideal intermediate day for model validation. The partial clear sky conditions occurred from 10am to 12am, causing a maximum solar irradiance of 600W/m^2 and the rest of the day remained overcast. The two curves illustrated in Figure 5-11 match well. The weather difference between Montreal and Varennes is small so no data points needed to be corrected for that day.



Figure 5-11 Measured global irradiance from Varennes compared to measured exterior horizontal illuminance from Montreal (May 16th 2009, intermediate day)

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Step 2: Compare model-calculated exterior façade vertical illuminance to measured

Figure 5-12 illustrates the comparison between the model-calculated and measured exterior façade vertical illuminance. The results match well throughout the day which confirms that the weather conditions in Montreal and Varennes were similar.



Figure 5-12 Model-calculated exterior façade vertical illuminance compared to measured (May 16th 2009, intermediate day)

Step 3: Compare illuminance level at three workplane measurement points

The comparison between model-calculated and measured workplane illuminance at 1m, 3m and 5m from the façade under intermediate sky conditions is illustrated in Figure 5-13, Figure 5-14 and Figure 5-15 respectively. For all three figures, relative errors are all within the range from -15% to +20%.







Figure 5-14 Model-calculated workplane illuminance at 3m from façade compared to measured (May 16th 2009, intermediate day)



Figure 5-15 Model-calculated workplane illuminance at 5m from façade compared to measured (May 16th 2009, intermediate day)

5.5.3 Case 3: May 13th, 2009 (Clear sky conditions)

It was difficult to find a completely clear day from morning until night for both Montreal and Varennes during the period from May 1st 2009 to July 1st 2009. May 13th 2009 was chosen for the validation of clear sky conditions because the weather was mostly clear for both Montreal and Varennes, and the sun was not shaded by clouds for most of the time.

Step 1: Compare sky conditions in Montreal and Varennes

Figure 5-16 shows the comparison of the measured global horizontal irradiance from Varennes with the measured exterior horizontal illuminance from Montreal. The two curves in the figure match well except for a few deviations at 12pm, 6pm and 7pm. The reason for the first deviation at 12pm was that a few scattered clouds shaded the sun in Montreal while the sun was not shaded in Varennes. This matches well with the information obtained from Environment Canada (Figure B-2 in Appendix B) that on May 13th, the sky conditions changed to mainly clear after 10am. The second large weather deviation, occurring at 6pm and 7pm was caused by the shading from a neighboring building. As illustrated in Figure 5-17, the shade of the building was moving towards the test hut in a sunny afternoon and the test hut was completely shaded by the building after 6pm.



Figure 5-16 Measured global irradiance from Varennes compared to measured exterior horizontal illuminance from Montreal (May 13th 2009, clear day) One data point with large weather deviation has been corrected



Figure 5-17 The shade of a neighbor building is approaching the test hut in a clear summer day afternoon

Step 2: Compare model-calculated exterior façade vertical illuminance to measured

Figure 5-18 illustrates the comparison between the model-calculated and measured exterior façade vertical illuminance. The results match well throughout the day. This step confirms that the Perez all-weather sky model is able to simulate the clear sky accurately.

During a clear day, the maximum illuminance level incident on the façade is more than 60,000 lux. Without a shading device, glare problems can easily impact negatively on occupants' daily activities.


Figure 5-18 Model-calculated exterior façade vertical illuminance compared to measured (May 13th 2009, clear day)

Step 3: Compare illuminance level at three workplane measurement points

The comparison between model-calculated and measured workplane illuminance at 1m, 3m and 5m from the façade is illustrated in Figure 5-19, Figure 5-20 and Figure 5-21 respectively. Relative error is calculated for each data point and used to show the accuracy of the mathematical model. For all three figures, relative errors are all within the range from -5% to +20%. It can be seen that for all three figures, the relative errors are mostly in the positive range. This implies that this mathematical model's trend to slightly overestimate the workplane illuminance level.



Figure 5-19 Model-calculated workplane illuminance at 1m from façade compared to measured (May 13th 2009, clear day)

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Figure 5-20 Model-calculated workplane illuminance at 3m from façade compared to measured (May 13th 2009, clear day)



Figure 5-21 Model-calculated workplane illuminance at 5m from façade compared to measured (May 13th 2009, clear day)

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Chapter 6: SIMULATION RESULTS

6.1 Introduction

The objective of developing the mathematical model for the three-section curtain wall façade with the newly designed VisionControl® window is to provide a simulation tool to investigate its daylighting performance. As described in Chapter 3, this mathematical model is able to estimate the workplane illuminance for a typical rectangular shaped office under different sky conditions. Building designer could benefit from this mathematical model.

In preliminary design stage, building designers could use this mathematical model to estimate the daylighting performance of a curtain wall façade design with the newly designed VisionControl® window under different design parameters such as:

- ➢ Building location
- > Façade orientation
- > Different type of louver used in the VisionControl® window
- > Façade geometry
- > Room interior surface reflectance
- Different control strategies

In order to show the future possible use of the mathematical model and illustrate what kind of information can be extracted from the simulation results, a number of simulations were conducted for different cities, façade orientations and control strategies.

For each simulated building location, hourly TMY2 (Typical Meteorological Year) weather data was used. This weather data was derived from the 1961-1990 National solar radiation database and was converted by TRNSYS16 into hourly weather

observations (Robinson 2009). The simulated annual daylighting performance results are presented in dynamic daylighting performance metrics: Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI).

6.2 Dynamic daylighting performance metrics

The advantage of using dynamic daylighting performance metrics is that they can be used for comparative studies to guide building designers, owners and users on effective decisions based on their daylight requirements (Kapsis 2009).

Daylight Autonomy (DA) uses workplane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone (Reinhart et al. 2006). In 2001, Reinhart and Walkenhorst (2001) redefined daylight autonomy as the percentage of the occupied times of the year when the minimum illuminance requirement (500 lux) at the sensor is met by daylight alone.

Useful Daylight Illuminance (UDI), proposed by Nabil and Mardaljevic (2006), is a dynamic daylight performance measure that is also based on workplane illuminances. It aims to determine when daylight levels are 'useful' for the occupant and also to distinguish if the daylight is in the too dark range, comfort range or the too bright range. Based on the upper and lower thresholds of 2,000lux and 100lux, UDI results in three ranges show the percentages of the occupied times of the year when the UDI was achieved (100-2,000lux), fell-short (<100lux), or was exceed(>2,000lux) (Reinhart et al. 2006).

6.3 Different building locations

Climate characteristics of a building location have a significant impact on the annual daylighting performance of a façade design. Four North American cities were selected in this comparison to investigate how the daylighting performance of the three-section façade with VisionControl® window varies with building locations. These cities were chosen based on latitude, climate characteristic and how well-known they are (major cities).

Based on the information provided by U.S. National Climatic Data Center, Phoenix, AZ (latitude 33.43°N) is the one of the sunniest cities in U.S. due to its arid climate with hot summers. On the other hand, Seattle, WA (latitude 47.6°N) is considered as one of the cloudiest cities in U.S. due to its oceanic climate (National Climatic Data Center 2009). San Francisco, CA (latitude 37.77°) is chosen because it is also located along the west coast of U.S. and located half way between Phoenix and Seattle. Montreal, QC is also chosen for the comparison because it has almost the same latitude as Seattle and it is considered to be a sunny city in Canada. A comparison of annual sunshine hours for Canadian cities and international cities is illustrated in Figure 6-1. Table 6-1 summarizes the four cities chosen for this study.





City name	Latitude	Reason
Phoenix, Arizona	33.43°	One of the sunniest cities in North America
San Francisco, California	37.77°	Latitude between Phoenix and Seattle
Montreal, Quebec	45.5°	One of the sunniest cities in Canada
Seattle, Washington	47.6°	One of the cloudiest cities in North America

Tal	ble	6-1	North	American	cities	selected	lin	the	compar	ison
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A base case office was used, to study the daylighting performance of the shade under the four different cities. The office is a 3m high, 3m wide and 6m deep room with an equally divided (horizontally) south facing 3m high three-section façade.

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VisionControl® windows with bright-dip anodized louvers are used on both top and middle sections of the façade. Details about the basic case office are summarized in Table 6-2.

Bright-dip anodized louver		
Equally divided 3m high three-section curtain wall façade		
South		
0.2 for floor and 0.7 for all other surfaces		
No direct sunlight can penetrate through the window at all		
times, top section controlled for maximum daylight		
transmittance, middle section controlled for best view to		
exterior.		

Table 6-2 Basic simulation settings (for different building locations)

Simulation results of daylight autonomy for all three U.S. cities with different latitudes are illustrated in Figure 6-2. Daylight autonomy was estimated at three distances away from the façade. Phoenix has the highest daylight autonomy results for all three measurement points due to having the lowest latitude and the sunniest climate. Seattle has the lowest daylight autonomy results due to its high latitude and cloudiest weather. It can be concluded that the daylight autonomy results are decreaing with the increase in latitude. Figure 6-3 illustrates the daylight autonomy comparison between Seattle and Montreal. It is interesting to observe that Montreal, which has almost the same latitude as Seattle, has much higher daylight autonomy. This can be explained by the fact that the climate in Montreal is much sunnier than that of Seattle.



Figure 6-2 Daylight autonomy comparison among selected cities



Figure 6-3 Daylight autonomy comparison among selected cities

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6.4 Different façade orientations

The movement of the sun from sun rise until sun set causes differences in the amount of daylight that can be received by the façade surfaces of a building. Façade orientation is important for the design of shading devices and the development of related control strategies.

The simulation case used in this study is similar to the room used in the previous study – a rectangular office with three-section curtain wall façade located in Montreal Canada. The simulation is repeated for 8 different façade orientations: S, SE, E, NE, N, NW, W and SW. Other details about the simulated office room are listed in Table 6-3.

Building location	Montreal		
Louver type	Bright-dip anodized louver		
Façade type	Equally divided 3m high three-section façade		
Room interior reflectance	0.2 for floor and 0.7 for all other surfaces		
	No direct sunlight at all times, top section controlled for		
Control strategy	maximum daylight transmittance, middle section		
	controlled for best view to exterior.		

Table 6-3 Basic simulation settings (for different façade orientations)

Figure 6-4 shows the daylight autonomy results for all eight façade orientations. For the point 1m from the façade, the result does not vary much with the orientation because it is easy to have an illuminance level higher than 500lux for a point that is close to the façade. For the point at 3m from the façade, daylight autonomy is slightly lower for North and West orientations due to less exposure to direct sunlight on clear days, but the differences are still small. For the point at 5m from the façade, it is obvious that the South orientation has the highest values in daylight autonomy. Daylight autonomy for the East orientation is slightly higher than that for the West orientation at the back of the room (5m from the façade). This might be due to the fact that it tends to be clearer in the morning than the afternoon because of lower temperatures and lower humidity. Daylight autonomy reaches the lowest value at North orientation due to the lowest exposure to direct sunlight. These results demonstrate that this mathematical model is able to simulate the daylight variation with façade orientations providing reasonable results. They also show that VisionControl® window with three-section façade concept could provide sufficient daylight to illuminate this 6m deep office with a minimum daylight autonomy higher than 0.6.



Figure 6-4 Daylight Autonomy (DA) result for different façade orientations in Montreal

Figure 6-5 presents the Useful Daylight Illuminance (UDI) results for 1m, 3m and 5m points from the façade. For UDI 2,000, the highest value appears at South orientation and the result is reduced with increase in distance from façade. However, for UDI 100-

2,000, the highest value appears at North orientation and the value increases with the distance from the façade. This shows that despite the South orientation having the highest level of daylight, most of the daylight lies in the 2,000+lux range rather than the 100-2,000 lux comfort range. For North orientation, despite less daylight availability, the majority of the daylight lies in the comfort range of 100-2,000 lux.



Figure 6-5 Useful Daylight Illuminance (UDI) results for different façade orientations in Montreal

6.5 Control strategies

Control strategy is another important factor which affects the daylighting performance of a façade design. More importantly, it protects the occupants from glare and provides them with the flexibility to control the integrated blinds to meet their individual need for daylighting.

Due to the possible complexity of this topic, two simplified control strategies are compared in this study in order to show the mathematical model's capability of considering different control strategies, as follows.

- Control strategy A: controls the top section for best daylighting performance and the middle section for maximum view to the exterior. No direct sunlight can penetrate façade at all times.
- Control strategy B: controls the top section for the best daylighting performance and keeps the middle section fully closed at all times for privacy. No direct sunlight can penetrate façade at all times.

Other basic simulation settings are listed in Table 6-4.

Building location	Montreal
Louver type	Bright-dip anodized louver
Room interior reflectance	0.2 for floor and 0.7 for all other surfaces
[°] Façade type	Equally divided 3m high three-section façade
Façade orientation	South

 Table 6-4 Basic simulation settings (for different control strategies)

Daylight autonomy results are shown in Figure 6-6. As expected, control strategy A has higher daylight autonomy results for all three measurement points than those for control strategy B due to more area of the façade being opened. Figure 6-7 illustrates the comparison of UDI (100-2,000 lux) for control strategy A and B. It is interesting to see that despite less daylight being available for control strategy B, more useful daylight illuminance lies in the comfort 100-2,000 lux range than that for control strategy A.

The two control strategies compared in this study are simple, without any complicated scheduling or consideration of any override actions from the occupants, but the results generated demonstrate that this mathematical model is capable of considering different control strategies. This mathematical model can be used as a performance evaluation tool for control strategies that are developed for the three-section façade with VisionControl® window in the future.



Figure 6-6 Daylight autonomy results for control strategy A and B





Chapter 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this thesis, the daylighting performance of the newly designed VisionControl® window with three-section curtain wall façade concept was studied and a daylight mathematical model was developed for simulating its daylighting performance. The studied three-section façade is composed of top daylighting section, middle viewing section and an opaque spandrel section. The newly designed VisionControl® windows are used on both the top and middle sections of the façade and the integrated rotatable louvers can be controlled independently for each section.

A custom-built testing device was designed and constructed in order to measure the visible transmittance of the newly designed VisionControl® window. This window's visible transmittance is one of the most important inputs to the mathematical daylighting model. For the measurement, special considerations were given to important parameters such as solar profile angles and the integrated louvers' tilt angles. This custom-built testing device utilizes two photometric sensors to measure the illuminance at the exterior surface of the window and ten sensors to measure the transmitted illuminance behind the window. The layout of the ten sensors behind the tested window was carefully designed and the spacing between each sensor was calculated to provide a situation equivalent to ten measurement points between two adjacent louvers. Due to these strategies, the total time required to measure the visible transmittance of the newly designed window was greatly reduced. Also, purchasing an expensive goniophotometer was avoided and the measured results show better accuracy than previous studies (compare to Tzempelikos 2002).

Tools for investigating the daylighting performance of advanced fenestration products with integrated controllable louvers are limited. Therefore, a mathematical daylighting model was developed based on the radiosity method. This model can be used to investigate the annual daylighting performance of the newly designed VisionControl® window in a specific three-section curtain wall façade design. Also, this model could be adapted for other similar advanced fenestration products. It considers several important design parameters, such as building location, façade orientation, geometry of the threesection façade and control strategy, to estimate the workplane illuminance distribution based on the input weather data. A control strategy for the three-section façade concept was also developed. It controls the louvers to maximize the visible transmittance and the view to the exterior while preventing direct sunlight from entering the space. If typical meteorological year weather data is used, annual daylighting performance can be estimated. Building designers could use this mathematical model to refine their designs by simulations with different settings in these design parameters. Annual dynamic daylighting performance metrics such as Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) can be compared easily with other daylighting designs.

An experiment was conducted to verify the developed mathematical daylighting model. This experiment utilized a 1:3 scale office model with a south facing three-section curtain wall façade. The newly designed VisionControl® window was used to cover both the top and middle sections of the façade. The interior workplane illuminance was measured and compared with the model-calculated results. Three representative days with typical overcast, intermediate and clear sky conditions were selected for the validation and the results are compared. Good agreement was observed under overcast

sky conditions and intermediate sky conditions with an error range of $\pm 25\%$. Under clear sky conditions, the model slightly overestimates the workplane illuminance, but within an error range of -5% to +20%.

Although this mathematical model could estimate workplane illuminance based on user specified inputs, there are also some limitations. First, the mathematical model is based on the radiosity method which assumes all surfaces are perfectly diffuse. For typical interior drywall surfaces, it is a valid assumption. Second, the model assumes no direct sunlight penetrating the window at all times. With the help of the integrated aluminum louver inside the VisionControl® window and an appropriate control strategy, direct sunlight can be easily blocked and diffused by inter-reflections between louvers before entering the interior. This assumption seems valid in this case and allows the use of the radiosity method. Last, this mathematical model is designed for an office with rectangular floor shape only. Any variation in the shape of floor plan or any other sources of daylighting, such as other openings in walls cannot be considered by this model.

The development of the new generation of VisionControl® window has been completed. The newly designed window shows a reduced overall thickness (1.5") which allows this advanced fenestration product to be used for standard curtain wall constructions and various retrofit projects. Various design considerations were implemented during the design stage, such as louver profile and surface finishes, in order to improve the product's daylighting performance.

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7.2 Recommendations for future work

The newly designed VisionControl® window allows this unique advanced fenestration product to be used as a standard component for curtain wall constructions and retrofit projects. Future research work could be conducted in the following areas:

- Glare protection and visual comfort.
- Solar heat gain calculation and interaction with HVAC control systems.
- Advanced occupancy-based control strategies for the three-section façade application.

Future work could focus on the determination of potential glare problems and address the important feedbacks to the control system. Other efforts could also focus on improving other aspects of visual comfort in the interior space.

Daylighting performance is the only performance index used in this study. No consideration was given to the potential solar heat gain induced by the introduced daylight. As an extension to the mathematical daylighting model, a radiation energy model combing both daylighting and solar heat gain would be interesting. Possible interactions between the daylighting façade control system and the HVAC control system could provide energy savings in cooling or heating the occupied space.

Advanced control strategies, such as occupancy-based control, could be developed to further reveal the potential of the newly designed VisionControl® window with the three-section curtain wall façade concept. Different scheduling of weekdays and weekends could provide more potential energy saving by offsetting the peak loads.

From the commercial point of view, developing a controller for the three-section façade with VisionControl® window will further enable this product's application in intelligent and green building designs, and help push the industry forward.

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Appendix A:

Redesign of VisionControl® window

A-1. Introduction & design objectives

In Chapter 2, the review of advanced fenestration products available today on the market and the comparison with VisionControl® window, gives us a clear idea of how this product fits into this competitive market. Keeping the good features from the previous generation and adding new value to the future generation is the ultimate objective of the development and design.

The following features of the VisionControl® window should be carried over to the next generation to distinguish this unique product from other advanced fenestration products:

- Louvers are operated by the patented mechanism hidden in the window spacer
 - 180° (approximate) louver rotatable angle
 - The self-reversing mechanism
- Thumbwheel, crank and motorized operations

To improve the VisionControl® window's performance in daylighting and widen its application in commercial curtain wall constructions and retrofit projects, the design objectives of the new generation of VisionControl® window are:

- Reducing the product's overall thickness from 2.5" to 1.5" (two panes of ¼" glazings used)
- Redesigning the operating mechanism to accommodate the new thickness
- Designing a new louver profile to accommodate the reduced overall thickness
- Providing variation in surface finishes to enhance the product's daylighting performance and offer choices in color

As shown in Figure A-1, in order to design a unit with overall thickness less than 1.5", the width of the air space should not exceed 1".



Figure A-1 Overall thickness of VisionControl®

The air space is where the spacer, aluminum louvers and operating mechanism are located. Reducing the width of the air space from 2" to 1" affects all the parts used in this product. Thus, all parts should be redesigned to accommodate the new overall thickness.

A-2. Design of the new louver

The louver is a key component in the VisionControl® window. Unfortunately, the old louver profile cannot simply be scaled down and used in the new product. The main reason for this is that the rigidity of the louver is not sufficient to support a span of 48" with acceptable deflection. It is possible to increase the thickness of the louver to increase its rigidity, however, the increased louver thickness would cause great reduction in the product's view to the exterior, or in other words, the width of the opening between two adjacent louvers will be reduced.

The following list summaries all the important aspects should be considered in the design of the new louver:

- Louver rigidity (sufficient for 48" span without noticeable curve under its own weight)
- Louver thickness
- Percentage of view to exterior
- Louver width
- Clearance between the glass and edge of louver
- Interlock between louvers
- Louver spacing

Clearance between the glass and edge of louver

Clearance between the glass pane and the edge of louver is a very important aspect in the louver design. In reality, the glass panes are never perfectly flat, but a little concave (or convex). On the other hand, the temperature change in the environment will cause pressure difference between inside and outside of the window because this product is hermetically sealed. Normally, this product is sealed at room temperature which is close to 22°C and thus, when we put the window in an environment which is lower than 22°C, the inner pressure will become lower than the ambient pressure. Under large temperature difference, such as in winter, the high pressure difference will push the center of the glass inward towards the louver. In this case, the clearance is extremely important because any contact between the louver and the glass will block the louver rotation and cause failure in the operating mechanism. A 1.5mm clearance on each side of the louver, as shown in Figure A-2, was judged to be enough to deal with this problem.



Figure A-2 Clearance between the glass pane and the edge of louver

The maximum width of louver can be calculated by:

width of air space -2 * clearance = Maximum louver width

Louver spacing and the "Interlock"

On the left and right ends of the louver profile, a channel called the interlock was designed to make sure the louvers could be closed tightly without any light leakage through the gap. This design enables the occupants to create a dark environment for video presentations or when privacy is needed. The interlocks on two adjacent louvers overlap with each other when louvers are operated at the fully closed position. The spacing of two adjacent louvers is determined by:

Louver spacing = *Louver width* - *width of interlock*

From the equation for calculating the louver spacing we see that higher width of interlock will result in smaller louver spacing.

View to the exterior

After the maximum louver width and louver spacing are determined, another important dimension of the louver – the louver thickness, is required to define the approximate size of the new louver design. As illustrated in Figure A-3, the calculation of the percentage of view to the exterior shows the relation between the louver spacing and the louver thickness. The maximum percentage of view to the exterior can be calculated by:

Maximum % of exterior view =
$$\frac{Louver spacing - Louver thickness}{Louver spacing}$$

This equation shows that in order to maximize the percentage of view to the exterior, we need to maximize the louver spacing and minimize the louver thickness. Based on experience, a maximum view to the exterior of 75%, when the louver is operated at the fully open position, is considered a good balance point between the louver thickness and louver spacing. When a good feeling of openness to the exterior is achieved, occupants may even ignore the presence of the louvers.



Figure A-3 Percentage of view to exterior

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Rigidity issue

The profile design of the new louver is mainly limited by the rigidity it can provide. The rigidity determines the deflection at the middle of the louver span due to its own weight (as illustrated in Figure A-4).



Figure A-4 Deflection under louver's own weight

The objective is to design a louver profile which can provide sufficient rigidity for a span length of 48". Sufficient rigidity means that the deflection at the middle point of the span is so small that it will not be "noticeable" by human eyes. This design objective is not clear because the amount of deflection that is not "noticeable" is subjective. For this problem, we conducted several small experiments such as placing plastic strips in front of different people and trying to find out if there is a common quantity of deflection at which people will start to notice the bent shape of the span. From these experiments, we found that the deflection at the middle of a 48" long span should not exceed 3mm to make sure that nobody would notice the deflection.

With this deflection in mind, the deflection of a span can be calculated by:

$$\Delta_{max} = \frac{W}{Coeff * E * I}$$

Where, W is the louver's own weight, E is the Yong's modulus of the material used for the louver, I is the moment of inertia provided by the louver profile and *Coeff* is a coefficient which varies with the type of supports at both ends of the span. Because the louver is supported by pivots which are inserted into the louver, this type of support is stronger than either a simply supported span or a clamp supported span, as illustrated in Figure A-5.

For the design trials, we needed to vary the materials used, the profile shapes and the types of supports, which are complicated cases for the determination of the deflection at the middle point of the span. Structural design simulation is considered the fastest and most effective way to determine the deflection for different design trials. Software known as CATIA® is used for the structural design of the louver profile (as shown in Figure A-6).



Simple support

Clamp support

Figure A-5 Simple and clamp supported spans



Figure A-6 Deflection of louver under its own weight (simulated by CATIA)

The preliminary design of louver with 0.8mm wall thickness is shown in Figure

A-7.

Figure A-7 Preliminary design of louver with 0.8mm wall thickness

Extrusion difficulty and manufacture selection:

The easiest process for manufacturing a hollowed aluminum louver is aluminum extrusion. From previous louver structural analyses, we found that the thinner the wall, the lower the deflection at the middle point of the span. However, the wall thickness is limited by the minimum thickness that can be produced by the aluminum extrusion method. After we sent the drawing of the preliminary louver design for price quotations, some aluminum extruders replied that the thickness of the wall was too thin to be extruded.

In the aluminum extrusion process, thinner wall thickness requires not only higher pressure in pushing the liquid aluminum through the die, but also reduces the service life of the die. 1.0-1.1mm is generally the standard minimum wall thickness for a hollow profile that can be extruded. Any dimension lower than 1mm will require higher level of equipment and generally higher cost. After spending a month searching for a manufacturer capable of extruding our louver profile with a wall thickness of 0.8mm and reasonable price, we found a company in Ontario which becomes the final provider of the new louver.

Louver surface finishes

After the extrusion problem was solved, we have to decide what kind of surface finish to provide with the new louver. Louver surface finish determines the optical properties of the louver, which in turn, affect the daylighting performance of this new fenestration product. Generally, when describing the reflection of from a surface, two performance indices are used:

Surface reflectance determined by surface material and color

• Surface specularity determined by the smoothness of the surface (at the microscopic level)

The louver surface will be exposed to direct sunlight which contains ultra-violet radiation. This could gradually change the optical properties of the surface (color etc.) Therefore, any surface finish used for the new louver should be ultra-violet stable.

Considering these design requirements, along with the cost of the surface finish process, we decided to offer three louver surface finishes as shown in Table A-1. Figure A-8 shows the photo of the three louver surface finishes.

Surface finish	Type of reflection	Features		
White paint	Intermediate	UV-stable		
	Internetiate	Various colors		
Bright-Dip anodized		UV-stable		
	Specular	Mirror-like smooth and shining		
		Natural color of aluminum		
Clear anodized		UV-stable		
	Diffuse	Rough surface (at the microscopic level)		
		Various colors		

Table A-1 Three louver surface finishes



Figure A-8 The photo of the three louver surface finishes offered
Dust accumulation in louver channels

Another issue was found after some samples of the new louver were received. As illustrated in the left picture of Figure A-9, the interlock channels were so small that it was easy for dust to accumulate in them during the assemble process. It was also difficult to clean the interlocks.



Figure A-9 Size of interlock channel (before and after modification)

To solve this problem, we modified the profile design again to increase the size of the channel (as shown in Figure A-9).

Final louver design:

Figure A-10 shows the final design of the louver profile. This louver profile is 5mm thick, 22.4mm wide with a wall thickness of 0.8mm. This 0.8mm wall thickness did not cause any extra cost to the extrusion process and the supplier is reasonably close to Montreal so no extra shipping costs were incurred. A sample of the louver conformed that this design was able to provide sufficient rigidity for a 48" span without noticeable deflection at the middle point of the span (as shown in Figure A-11). For this louver design, three surface finishes are provided, covering three types of reflectivity – diffuse, intermediate and specular. All three surface finishes provide the customer with the freedom to choose any color. With a louver spacing of 21.2mm, this louver design is able to provide a 76.4% of view to exterior when the louvers are in the fully open position. The specifications for the final louver profile design are summarized in Table A-2.



Figure A-10 Final design of louver profile



Figure A-11 Louver profile design shows sufficient rigidity for a 48" long span

Louver width	22.4mm
Louver thickness	5mm
Louver spacing	21.2mm
Clearance from glass to louver	1.5mm
Size of interlock	1.2mm
Maximum % of view to the exterior	76.4%
Wall thickness	0.8mm
Material	Aluminum 6163
Temper method	Т5
Maximum span length	48"

Table A-2 Specifications of the final louver design

Appendix B:

Weather data from Environment Canada

(For days chosen for model verification)

					QUE	DEC .			
ļ	45° 28.000	'N		Longitude	: 73° 45.000	Elevation: 36.00 m			
<u>Climate ID</u> : 7025250 <u>WMO 1</u>						: 71627		TC ID:	YUL
Previou	<u>is Day</u>		June		• 9 •	2009 🛨	Go		<u>Next Day</u>
			Hour	ly Data	a Repor	t for June	9, 2009)	÷
Т	Temp	Dew	Rel	Wind	Wind	Visibility	<u>Stn</u>	Hmdx Wind	<u>Weather</u>
Ĩ	٥C	Point	Hum	Dir	Spd	km	<u>Press</u>	<u>Chill</u>	
m	2	Temp	%	10's	km/h	A	kPa	and the second sec	ali si 1877
e		°C ⊠	M	deg	M		· 2051		
00:00	14.8	4.2	49	10	9	25.0	101.11		Cloudy
01:00	14.6	4.3	50	8	13	25.0	101.07		Cloudy
02:00	14.5	3.8	49	8	17	25.0	101.01		Cloudy
03:00	13.8	5.1	56	10	15	25.0	100.95		Rain Showers
04:00	13.0	6.2	63	9	11	19.3	100.92		Rain
05:00	12.2	6.8	70	7	13	19.3	100.92	· · ·	Rain
06:00	11.4	7.7	78	8	19	19.3	100.86		Rain
07:00	11.3	8.7	84	6	17	12.9	100.84		Rain
08:00	11.6	9.8	89	9	15	9.7	100.77		Rain, Fog
09:00	11.8	9.9	88	8	30	12.9	100.67		Rain
10:00	12.1	10.4	89	9	17	9.7	100.66		Rain, Fog
11:00	12.3	10.6	89	8	24	4.0	100.56		Rain, Fog
12:00	12.5	10.9	90	8	20	12.9	100.47		Rain
13:00	13.0	11.1	88	· . 5	15	16.1	100.45		Cloudy
14:00	13.9	12.1	89	6	15	19.3	100.38		Cloudy
15:00	14.3	.12.2	87	6	13	19.3	100.39		Cloudy
16:00	15.4	12.9	85	3	7	19.3	100.40		Cloudy
17:00	14.6	13.1	91	36	7	11.3	100.37		Rain Showers
18:00	13.4	12.1	92	31	11	9.7	100.44		Drizzle
19:00	13.0	11.8	92	32	7	11.3	1 00. 49		Cloudy
20:00	12.5	11.2	92	31	7	11.3	100.55		Cloudy
21:00	12.5	11.0	91	34	6	11.3	100.62		Cloudy
22:00	12.4	11.1	92	·30	4	12.9	100.71		Cloudy
23:00	12.6	11.2	91	28	4	12.9	100.76		Cloudy

MONTREAL/PIERRE ELLIOTT TRUDEAU INTL A QUEBEC

Figure B-1 Weather condition for June 9th 2009 in Montreal

	<u>Latitude</u> : -	45° 28.000	I'N		Longitude	₽73°45.000)' W	El	evation:	36.00 m
<u>c</u> ı	imete ID;	7025250			WMO ID	:71627			<u>TC ID</u> : Y	YUL
Previo	us Day		Мау		16 🕃	2009 💽	Go			<u>Next Day</u>
· ·			Hourl	y Data	Report	for May 1	6, 200	9		
T i m e	<u>Temp</u> °C ☑	Dew Point Temp °C Ø	Rel Hum ⋈	<u>Wind</u> <u>Dir</u> 10's deg	<u>Wind</u> Spd km/h ⊠	<u>Visibility</u> km ☑	Stn Press kPa Ø	<u>Hmdx</u>	<u>Wind</u> Chill	<u>Weather</u>
00:00	11.9	6.4	69		0	25.0	101.86			Cloudy
01:00	9.3	5.8	79	5	4	25.0	101.82			Mostly Cloudy
02:00	10.8	5.6	70	4	9	25.0	101.79			Mostly Cloudy
03:00	11.0	6.1	72	3	11	25.0	101.71			Mostly Cloudy
04:00	11.7	5.8	67	5	11	24.1	101.68			Cloudy
05:00	11.6	:4.9	63	11	11	48.3	101.67	e eg		Cloudy
06:00	12.4	5.2	61	8	13	48.3	101.62			Cloudy
07:00	13.0	5.2	59	- 8	13	48.3	101.51			Cloudy
08:00	14.4	4.9	53	9	20	48.3	101.37			Cloudy
09:00	15.5	5.9	53	9	19	48.3	101.16			Cloudy
10:00	17.9	6.4	47	12	24	48.3	100.99	d		Cloudy
11:00	19.0	6.7	45	12	22	24.1	100.86		s	Cloudy
12:00	14.2	11.3	83	13	26	9.7	100.75			Rain, Fog
13:00	13.9	11.5	85	13	26	19.3	100.64			Rain
14:00	14.1	11.9	87	14	32	19.3	100.48			Rain
15:00	14.6	12.3	8 6	14	30	6.4	100.35	· · · · ·		Rain, Fog
16:00	14.9	13.1	89	19	6	8.0.	100.40			Rain, Fog
17:00	15.1	13.7	91	14	19	4.8	100.27	· · ·		Rain, Fog
18:00	15.5	14.1	91	15	22	8.0	100.24			Rain, Fog
19:00	15.6	14.3	92	16	15	12.9	100.20			Rain
20:00	16.1	14.6	91	16	17	16.1	100.18			Rain
21:00	17.0	15.3	90	19	15	19.3	100,17			Rain
22:00	17.0	15.0	88	22	17	25.0	100.17			Cloudy
23:00	16.6	14.7	89	23	20	25.0	100.15		·	Cloudy

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Figure B-2 Weather condition for May 16th 2009 in Montreal

ļ	Latitude:	45° 28.000	'N		Longitude	: 73° 45.000	' W	Elevation:	36.00 m
<u>Climate ID</u> : 7025250 <u>WMO ID</u> : 71627 <u>TC ID</u> : Y								YUL	
Previou	is Day		May		13 🝷	2009 🔫	Go		<u>Next Day</u>
Hourly Data Report for May 13, 2009									
T I m	<u>Temp</u> °C ☑	<u>Dew</u> <u>Point</u> <u>Temp</u>	<u>Rel</u> Hum %	<u>Wind</u> <u>Dir</u> 10's	<u>Wind</u> <u>Spd</u> km/h	<u>Visibility</u> km ⊠	<u>Stn</u> Press kPa	<u>Hmdx Wind</u> <u>Chill</u>	<u>Weather</u>
e		2° 17	M	deg	M		M.		
00:00	9.6	2.5	61	20	6	25.0	102.03		Clear
01:00	9.8	2.7	61	- 23	9	25.0	102.09		Clear
02:00	8.5	1.4	61	23	15	25.0	102.18		Clear
03:00	8.8	1.2	59	23	11	25.0	102.23		Clear
04:00	8.5	2.8	67	22	9	25.0	102.26		Clear
05:00	7.5	1.5	66		0	25.0	102.27		Clear
06:00	9.0	3.5	68	26	б	48.3	102.33		Clear
07:00	11.4	0.8	48	22	9	48.3	102.37		Clear
08:00	12.7	0.6	43	21	7	48.3	102.39		Clear
09:00	14.6	0.3	38	22	9	48.3	102.41		Clear
10:00	16.6	2.1	38	17	7	48.3	102.38		Mainly Clear
11:00	18.1	1.7	33	15	15	48.3	102.30		Mainly Clear
12:00	18.5	-0.7	27	19	7	48.3	102.27		Mainly Clear
13:00	19.0	-0.7	26	16	6	48.3	102.20	e Bernaria India Bernaria	Mainly Clear
14:00	19.6	1.2	29	19	6	48.3	102.10		Clear
15:00	19.5	0.6	28	13	4	48.3	102.02	· · · · ·	Mainly Clear
16:00	20.1	1.6	29	15	20	48.3	101.96		Mainly Clear
17:00	20.0	2.3	31	14	17	48.3	101.87		Mainly Clear
18:00	19.7	0.6	28	16	20	48.3	101.83		Main ly Clear
19:00	18.2	-1.3	27	15	15	48.3	101.81		Mainly Clear
20:00	17.3	-0.2	30	15	19	24.1	101.76	i	Clear
21:00	16.2	1.0	36	17	20	25.0	101.72		Mainly Clear
22:00	15.9	1.2	37	17	24	25.0	101.69	i i i i i i i i i i i i i i i i i i i	Clear
23:00	15.5	1.6	39	17	24	25.0	101.62		Clear

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Figure B-3 Weather condition for May 13th 2009 in Montreal

Appendix C:

Mathematical daylighting model of three-section façade with the newly

designed VisionControl® window

Simulation inputs

Building location inputs: (Montreal data used here)

$L := 45.5 \cdot deg$	Latitude
2	

$LNG := 74 \cdot deg$	Longitude

 $STM := 75 \cdot deg$

...Local standard time meridian

Office room geometry inputs:



 $H_{rm} := 3 \cdot m$...height of room

 $W_{glass} := W_{rm} - W_{mu} N_v$

 $W_{mu} := 10 cm$...width of each curtain wall mullion

 $N_{V} := 2$...number of vertical mullion

...width of the glass region

Facade orientation inputs:

 $\beta_{\rm W} := 90 \deg$

...facade tilt angle

 $\psi := 0 \cdot \deg$

...facade azimuth

Facade geometry inputs:



Surface reflectance inputs:

$\rho_{\text{floor}} := 0.70$	floor reflectance
$ \rho_{\text{ceiling}} := 0.70 $	ceiling reflectance
$ \rho_{\text{wall}} := 0.70 $	wall reflectance
$ \rho_{top} := 0.05 $	top section reflectance
$ \rho_{\text{mid}} \coloneqq 0.05 $	middle section reflectance
$\rho_{sp} := 0.70$	spandral section reflectance

Other inputs:

H _{workplane} := 0.8 m	height of the workplane from the floor
Interval _{angle} := 15deg	blind tilt angle controllable interval
limit:=100 $\frac{\text{watt}}{\text{m}^2}$	direct normal irradiance level limit to separate overcast and clear sky conditions

Select day of the year:

n := 1...365for annual simulation use 1...365for daily simulation use the number of the day

Select time of the day

starttime	:= 7	endtime	:= 17	based on your assumption of occupied hour

t := starttime .. endtime



Solar geometry



Solar geometry (Athienitis, 1993)

$$\begin{split} & \underline{\mathsf{Equation of time}\;(\underline{\mathsf{ET}}):} \\ & \mathrm{ET}(n) := \left(9.87 \cdot \sin\left(4 \cdot \pi \cdot \frac{n-81}{364}\right) - 7.53 \cdot \cos\left(2 \cdot \pi \cdot \frac{n-81}{364}\right) - 1.5 \cdot \sin\left(2 \cdot \pi \cdot \frac{n-81}{364}\right)\right) \cdot \min \\ & \underline{\mathsf{Apparent Solar Time}\;(\underline{\mathsf{AST}}):} \\ & \mathrm{AST}(n,t) := t \cdot \mathrm{hr} + \mathrm{ET}(n) + \frac{(\mathrm{STM}-\mathrm{LNG}) \cdot \mathrm{hr}}{15 \cdot \mathrm{deg}} \\ & \underline{\mathsf{Solar declination}\;(d):} \\ & \delta(n) := 23.45 \, \mathrm{deg} \cdot \sin\left(360 \, \frac{284 + n}{365} \cdot \mathrm{deg}\right) \\ & \underline{\mathsf{Hour angle}\;(\mathsf{H}):} \\ & \mathrm{H}(n,t) := (\mathrm{AST}(n,t) - 12 \, \mathrm{hr}) \cdot \left(15 \, \frac{\mathrm{deg}}{\mathrm{hr}}\right) \\ & \underline{\mathsf{Sunset hour angle}\;(h_{s}):} \\ & \mathrm{h}_{S}(n) := (\operatorname{acos}(-\tan(\mathrm{L}) \cdot \tan(\delta(n)))) \end{split}$$

Sunset time (t_s):

$$t_{s}(n) := h_{s}(n) \cdot \frac{hr}{15 \cdot deg}$$

Surface sunset time (t_{ss}):

$$t_{SS}(n) := \min\left(\left(h_{S}(n) \ \operatorname{acos}\left(-\tan\left(L - \beta_{W}\right) \cdot \tan\left(\delta(n)\right)\right)\right)\right) \cdot \frac{hr}{15 \cdot deg}$$

Solar altitude (α_s):

$$\alpha_{S}(n,t) := \begin{bmatrix} \operatorname{asin} \left[(\cos(L)) \cdot \cos(\delta(n)) \cdot \cos(H(n,t)) \dots \right] & \text{if } \operatorname{asin} \left[(\cos(L)) \cdot \cos(\delta(n)) \cdot \cos(H(n,t)) \dots \right] > 0 \text{ deg} \\ + (\sin(L)) \cdot \sin(\delta(n)) & 0 \text{ deg } \text{ otherwise} \end{bmatrix}$$

Solar azimuth (f):

$$\phi(n,t) := \operatorname{acos}\left(\frac{\sin(\alpha_{s}(n,t)) \cdot \sin(L) - \sin(\delta(n))}{\cos(\alpha_{s}(n,t)) \cdot \cos(L)}\right) \cdot \frac{H(n,t)}{|H(n,t)|}$$

 $\frac{Surface \ solar \ azimuth \ (g):}{\gamma \left(n,t\right):=\varphi \left(n,t\right)-\psi }$

Zenith angle (Z):

 $Z(n,t) := a\cos\left((\cos(L) \cdot \cos(\delta(n)) \cdot \cos(H(n,t)) + \sin(L) \cdot \sin(\delta(n)))\right)$

Angle of incidence (θ):

$$\begin{aligned} \theta\theta(n,t) &:= \cos\left(\alpha_{s}(n,t)\right) \cdot \cos\left(\left|\gamma(n,t)\right|\right) \cdot \sin\left(\beta_{w}\right) + \sin\left(\alpha_{s}(n,t)\right) \cdot \cos\left(\beta_{w}\right) \\ \theta(n,t) &:= \cos\left(\frac{\theta\theta(n,t) + \left|\theta\theta(n,t)\right|}{2}\right) \end{aligned}$$

Profile angle (λ):

$$\lambda(n,t) := \left| \begin{array}{l} \operatorname{atan} \left(\frac{\operatorname{tan} \left(\alpha_{S}(n,t) \right)}{\cos(\gamma(n,t))} \right) & \text{if } -90 \text{deg} < \gamma(n,t) < 90 \text{deg} \\ 90 \text{deg otherwise} \end{array} \right|$$

Calculated solar angles for n=188 (July, 7th) (Summer example)



Calculated solar angles for n=20 (Jan, 20th) (Winter example)



Perez Irradiance model (developed by Dr. A.Tzempelikos)

 $\rho_g(n,t) := \begin{bmatrix} 0.6 & \text{if } T_0(n,t) \le 3 \land (120 > n \lor n > 243) \\ 0.2 & \text{otherwise} \end{bmatrix}$ Ground reflectance:

Extraterrestrial solar radiation (outside the atmosphere):

Solar constant:

$$I_{sc} := 1367 \frac{W}{m^2}$$

Normal extraterrestrial solar radiation:

$$I_{exn}(n) := I_{sc} \cdot \left(1 + 0.033 \cos\left(\frac{360 n}{365} \cdot deg\right) \right)$$

Global horizontal irradiance:

 $I_{h}(n,t) := I_{bh}(n,t) + I_{dh}(n,t)$

Incident beam radiation on an inclined surface:

 $I_{b}(n,t) := \left(I_{bn}(n,t) \cdot \cos(\theta(n,t))\right)$

Perez diffuse irradiance model:

Diffuse radiation consists of three components:

Isotropic part, received uniformly from all the sky dome

Circumsolar diffuse, resulting from forward scattering of solar radiation and concentrated in the part of the sky around the sun.

Horizon brightening, concentrated near the horizon, most pronounced in clear skies.

Horizon brightness coefficients:

$$a_{\mathbf{p}}(\mathbf{n},\mathbf{t}) := \max(0,\cos(\theta(\mathbf{n},\mathbf{t})))$$

 $b_{\mathbf{p}}(\mathbf{n},t) := \max\left(\cos(85 \cdot \deg), \sin(\alpha_{s}(\mathbf{n},t))\right)$

Relative optical air mass:

mopt

$$(n,t) := \frac{\pi}{\sin(\alpha_{s}(n,t)) + 0.15\left(\alpha_{s}(n,t) \cdot \frac{\pi}{180 \deg} + 3.885\right)^{-1.253}}$$

1

Sky brightness:

$$\Delta(\mathbf{n}, \mathbf{t}) \coloneqq \mathsf{m}_{\text{opt}}(\mathbf{n}, \mathbf{t}) \cdot \frac{\mathsf{I}_{dh}(\mathbf{n}, \mathbf{t})}{\mathsf{I}_{exn}(\mathbf{n})}$$

Sky clearness:

$$\epsilon(n,t) := \begin{cases} \frac{I_{dh}(n,t) + I_{bn}(n,t)}{I_{dh}(n,t)} + 5.53510^{-6} \cdot (90 \cdot \deg - \alpha_{s}(n,t))^{3} \\ \frac{I_{dh}(n,t)}{1 + 5.53510^{-6} \cdot (90 \cdot \deg - \alpha_{s}(n,t))^{3}} & \text{if } I_{dh}(n,t) > 0 \cdot \frac{W}{m^{2}} \\ 0 & \text{otherwise} \end{cases}$$

Statistically derived irradiance coefficients for Perez model:

$$\begin{array}{lll} f_{11}(n,t) := & \begin{array}{c} -0.008 & \mbox{if } \epsilon(n,t) \leq 1.065 & f_{12}(n,t) := & 0.588 & \mbox{if } \epsilon(n,t) \leq 1.065 \\ 0.130 & \mbox{if } 1.065 < \epsilon(n,t) \leq 1.23 & 0.683 & \mbox{if } 1.065 < \epsilon(n,t) \leq 1.23 \\ 0.330 & \mbox{if } 1.23 < \epsilon(n,t) \leq 1.5 & 0.487 & \mbox{if } 1.23 < \epsilon(n,t) \leq 1.5 \\ 0.568 & \mbox{if } 1.5 < \epsilon(n,t) \leq 1.95 & 0.187 & \mbox{if } 1.5 < \epsilon(n,t) \leq 1.95 \\ 0.873 & \mbox{if } 1.95 < \epsilon(n,t) \leq 2.8 & -0.392 & \mbox{if } 1.95 < \epsilon(n,t) \leq 2.8 \\ 1.132 & \mbox{if } 2.8 < \epsilon(n,t) \leq 4.5 & -1.237 & \mbox{if } 2.8 < \epsilon(n,t) \leq 4.5 \\ 1.060 & \mbox{if } 4.5 < \epsilon(n,t) \leq 6.2 & -1.600 & \mbox{if } 4.5 < \epsilon(n,t) \leq 6.2 \\ 0.678 & \mbox{otherwise} & -0.327 & \mbox{otherwise} \end{array}$$

$$\begin{array}{lll} f_{13}(n,t) := & \begin{array}{c} -0.062 & \mathrm{if} \ \epsilon(n,t) \leq 1.065 & f_{21}(n,t) := & \begin{array}{c} -0.060 & \mathrm{if} \ \epsilon(n,t) \leq 1.065 & \\ -0.151 & \mathrm{if} \ 1.065 < \epsilon(n,t) \leq 1.23 & \\ -0.221 & \mathrm{if} \ 1.23 < \epsilon(n,t) \leq 1.5 & \\ -0.295 & \mathrm{if} \ 1.5 < \epsilon(n,t) \leq 1.95 & \\ -0.362 & \mathrm{if} \ 1.95 < \epsilon(n,t) \leq 2.8 & \\ -0.412 & \mathrm{if} \ 2.8 < \epsilon(n,t) \leq 4.5 & \\ -0.359 & \mathrm{if} \ 4.5 < \epsilon(n,t) \leq 6.2 & \\ -0.25 & \mathrm{otherwise} & \end{array}$$

Brightness coefficients:

$$\begin{split} F_{1}(n,t) &:= \max \Biggl[0, f_{11}(n,t) + f_{12}(n,t) \cdot \Delta(n,t) + \pi \cdot \frac{\left(90 \text{ deg} - \alpha_{s}(n,t)\right)}{180 \text{ deg}} \cdot f_{13}(n,t) \Biggr] \\ F_{2}(n,t) &:= \max \Biggl[0, f_{21}(n,t) + f_{22}(n,t) \cdot \Delta(n,t) + \pi \cdot \frac{\left(90 \text{ deg} - \alpha_{s}(n,t)\right)}{180 \text{ deg}} \cdot f_{23}(n,t) \Biggr] \end{split}$$

Sky diffuse radiation on a tilted surface:

$$I_{ds}(n,t) := I_{dh}(n,t) \cdot \left[\left(1 - F_1(n,t)\right) \cdot \left(\frac{1 + \cos\left(\beta_w\right)}{2}\right) + F_1(n,t) \cdot \frac{a_P(n,t)}{b_P(n,t)} + F_2(n,t) \cdot \sin\left(\beta_w\right) \right]$$

Ground-reflected radiation on a tilted surface:

$$I_{dg}(n,t) := I_{h}(n,t) \cdot \rho_{g}(n,t) \cdot \frac{1 - \cos(\beta_{w})}{2}$$

Total diffuse radiation on a tilted surface:

$$I_{d}(n,t) := I_{ds}(n,t) + I_{dg}(n,t)$$

The total incident solar radiation on a tilted surface:

 $\mathbf{I}(\mathbf{n},t) \coloneqq \mathbf{I}_{b}(\mathbf{n},t) + \mathbf{I}_{ds}(\mathbf{n},t) + \mathbf{I}_{dg}(\mathbf{n},t)$

Solar radiation on facade surface for n=188 (July, 7th) (Summer example)





Total

Switch from function of time to time array:

Solar Radiation:Outside temperature: $I_{ds_{t,n}} := I_{ds}(n,t)$ $T_{o_{t,n}} := T_{o}(n,t)$ $I_{t,n} := I(n,t)$ $I_{b_{t,n}} := I_{b}(n,t)$ $I_{d_{t,n}} := I_{d}(n,t)$ $I_{dg_{t,n}} := I_{dg}(n,t)$

Perez Illuminance model

Luminous efficacy coefficients:

- ab(n,t) := 57.20 if $\epsilon(n,t) \le 1.065$ 98.99 if $1.065 < \epsilon(n,t) \le 1.23$ 109.83 if $1.23 < \epsilon(n,t) \le 1.5$ 110.34 if $1.5 < \epsilon(n,t) \le 1.95$ 106.36 if $1.95 < \epsilon(n,t) \le 2.8$ 107.19 if $2.8 < \epsilon(n,t) \le 4.5$ 105.75 if $4.5 < \epsilon(n,t) \le 6.2$ 101.18 otherwise
- $cb(n,t) := \begin{array}{l} -2.98 & \text{if } \epsilon(n,t) \leq 1.065 \\ \\ -1.21 & \text{if } 1.065 < \epsilon(n,t) \leq 1.23 \\ \\ -1.71 & \text{if } 1.23 < \epsilon(n,t) \leq 1.5 \\ \\ -1.99 & \text{if } 1.5 < \epsilon(n,t) \leq 1.95 \\ \\ -1.75 & \text{if } 1.95 < \epsilon(n,t) \leq 2.8 \\ \\ -1.51 & \text{if } 2.8 < \epsilon(n,t) \leq 4.5 \\ \\ -1.26 & \text{if } 4.5 < \epsilon(n,t) \leq 6.2 \\ \\ -1.10 & \text{otherwise} \end{array}$

Diffuse luminous efficacy:

ad(n,t) :=	97.24 if $\epsilon(n,t) \le 1.065$	bd
	107.22 if $1.065 < \epsilon(n, t) \le 1.23$	
	104.97 if $1.23 < \varepsilon(n, t) \le 1.5$	
	102.39 if $1.5 < \varepsilon(n, t) \le 1.95$	
	100.71 if $1.95 < \varepsilon(n, t) \le 2.8$	
	106.42 if $2.8 < \epsilon(n,t) \le 4.5$	
	141.88 if $4.5 < \varepsilon(n, t) \le 6.2$	
	152.23 otherwise	
cd(n,t) :=	12.00 if $\epsilon(n,t) \le 1.065$	dd
	0.59 if $1.065 < \epsilon(n, t) \le 1.23$	
	-5.53 if $1.23 < \epsilon(n,t) \le 1.5$	
	-13.95 if $1.5 < \epsilon(n,t) \le 1.95$	
	-22.75 if $1.95 < \varepsilon(n,t) \le 2.8$	

-36.15 if $2.8 < \varepsilon(n,t) \le 4.5$ -53.24 if $4.5 < \varepsilon(n,t) \le 6.2$

-45.27 otherwise

Direct luminous efficacy:

- $bb(n,t) := \begin{array}{l} -4.55 & \text{if } \epsilon(n,t) \le 1.065 \\ -3.46 & \text{if } 1.065 < \epsilon(n,t) \le 1.23 \\ -4.90 & \text{if } 1.23 < \epsilon(n,t) \le 1.5 \\ -5.84 & \text{if } 1.5 < \epsilon(n,t) \le 1.95 \\ -3.97 & \text{if } 1.95 < \epsilon(n,t) \le 2.8 \\ -1.25 & \text{if } 2.8 < \epsilon(n,t) \le 4.5 \\ 0.77 & \text{if } 4.5 < \epsilon(n,t) \le 6.2 \\ 1.58 & \text{otherwise} \end{array}$
- $db(n,t) := \begin{cases} 117.12 & \text{if } \epsilon(n,t) \le 1.065 \\ 12.38 & \text{if } 1.065 < \epsilon(n,t) \le 1.23 \\ -8.81 & \text{if } 1.23 < \epsilon(n,t) \le 1.5 \\ -4.56 & \text{if } 1.5 < \epsilon(n,t) \le 1.95 \\ -6.16 & \text{if } 1.95 < \epsilon(n,t) \le 2.8 \\ -26.73 & \text{if } 2.8 < \epsilon(n,t) \le 4.5 \\ -34.44 & \text{if } 4.5 < \epsilon(n,t) \le 6.2 \\ -8.29 & \text{otherwise} \end{cases}$

 $d(n,t) := \begin{array}{l} -0.46 \quad \text{if } \epsilon(n,t) \leq 1.065 \\ 1.15 \quad \text{if } 1.065 < \epsilon(n,t) \leq 1.23 \\ 2.96 \quad \text{if } 1.23 < \epsilon(n,t) \leq 1.5 \\ 5.59 \quad \text{if } 1.5 < \epsilon(n,t) \leq 1.95 \\ 5.94 \quad \text{if } 1.95 < \epsilon(n,t) \leq 2.8 \\ 3.83 \quad \text{if } 2.8 < \epsilon(n,t) \leq 4.5 \\ 1.90 \quad \text{if } 4.5 < \epsilon(n,t) \leq 6.2 \\ 0.35 \quad \text{otherwise} \end{array}$

dd(n,t) :=	-8.91 if $\epsilon(n,t) \le 1.065$
	-3.95 if $1.065 < \epsilon(n,t) \le 1.23$
	-8.77 if $1.23 < \epsilon(n,t) \le 1.5$
	-13.90 if $1.5 < \varepsilon(n,t) \le 1.95$
	-23.74 if $1.95 < \varepsilon(n,t) \le 2.8$
	-28.83 if $2.8 < \epsilon(n,t) \le 4.5$
	-14.03 if $4.5 < \varepsilon(n,t) \le 6.2$
	-7.98 otherwise

Precipitable water content:

 $WC(n,t) := e^{0.07 \cdot T_{dp}(n,t) - 0.075}$

Diffuse horizontal illuminance:

$$E_{dh}(n,t) := I_{dh}(n,t) \cdot \left(\begin{array}{c} ad(n,t) + bd(n,t) \cdot WC(n,t) + cd(n,t) \cdot sin(\alpha_{s}(n,t)) \dots \\ + dd(n,t) \cdot ln(\Delta(n,t) + 10^{-10}) \end{array} \right) \cdot lx \frac{m^{2}}{W}$$

Direct normal illuminance:

$$E_{bn}(n,t) := \max \left[0, I_{bn}(n,t) \begin{bmatrix} ab(n,t) + bb(n,t) \cdot WC(n,t) \dots \\ 5.73 \cdot \left(90 \cdot deg - \alpha_{s}(n,t)\right) \cdot \frac{\pi}{180 \cdot deg} - 5 \\ + cb(n,t) \cdot e + db(n,t) \cdot \Delta(n,t) \end{bmatrix} \cdot \left[k \frac{m^{2}}{W} \right]$$

Direct horizontal illuminance:

Global horizontal illuminance:

$$E_{bh}(n,t) := E_{bn}(n,t) \cdot \sin(\alpha_s(n,t))$$

$$E_{h}(n,t) := E_{bh}(n,t) + E_{dh}(n,t)$$

Beam illuminance on a tilted surface:

 $E_{b}(n,t) := \left(E_{bn}(n,t) \cdot \cos(\theta(n,t))\right)$

Statistically derived illuminance coefficients for Perez model:

f ₁₁ (n,t) :=	0.011 if $\epsilon(n,t) \le 1.065$	$f_{12}(n,t) :=$	0.570 if $\epsilon(n,t) \le 1.065$
	0.429 if $1.065 < \epsilon(n,t) \le 1.23$		0.363 if $1.065 < \varepsilon(n,t) \le 1.23$
	0.809 if $1.23 < \epsilon(n,t) \le 1.5$		-0.054 if $1.23 < \epsilon(n,t) \le 1.5$
	1.014 if $1.5 < \varepsilon(n,t) \le 1.95$		-0.252 if $1.5 < \varepsilon(n,t) \le 1.95$
	1.282 if $1.95 < \varepsilon(n,t) \le 2.8$		-0.420 if $1.95 < \varepsilon(n,t) \le 2.8$
	1.426 if $2.8 < \varepsilon(n,t) \le 4.5$,	-0.653 if $2.8 < \varepsilon(n,t) \le 4.5$
	1.485 if $4.5 < \varepsilon(n,t) \le 6.2$		-1.214 if $4.5 < \varepsilon(n,t) \le 6.2$
	1.170 otherwise		-0.300 otherwise

$$\begin{split} f_{13}(n,t) &\coloneqq & -0.081 & \text{if } \epsilon(n,t) \leq 1.065 & f_{21}(n,t) \coloneqq & -0.095 & \text{if } \epsilon(n,t) \leq 1.065 \\ -0.307 & \text{if } 1.065 < \epsilon(n,t) \leq 1.23 & 0.050 & \text{if } 1.065 < \epsilon(n,t) \leq 1.23 \\ -0.442 & \text{if } 1.23 < \epsilon(n,t) \leq 1.5 & 0.275 & \text{if } 1.23 < \epsilon(n,t) \leq 1.5 \\ -0.531 & \text{if } 1.5 < \epsilon(n,t) \leq 1.95 & 0.380 & \text{if } 1.95 < \epsilon(n,t) \leq 1.95 \\ -0.689 & \text{if } 1.95 < \epsilon(n,t) \leq 2.8 & 0.425 & \text{if } 2.8 < \epsilon(n,t) \leq 2.8 & 0.425 & \text{if } 2.8 < \epsilon(n,t) \leq 4.5 & 0.411 & \text{if } 4.5 < \epsilon(n,t) \leq 4.5 & 0.518 & \text{otherwise} \end{split}$$

Brightness coefficients:

$$F_{1}(n,t) := \max\left[0, f_{11}(n,t) + f_{12}(n,t) \cdot \Delta(n,t) + \pi \cdot \frac{\left(90 \text{ deg } - \alpha_{s}(n,t)\right)}{180 \text{ deg}} \cdot f_{13}(n,t)\right]$$

$$F_{2}(n,t) := \max\left[0, f_{21}(n,t) + f_{22}(n,t) \cdot \Delta(n,t) + \pi \cdot \frac{\left(90 \text{ deg } - \alpha_{s}(n,t)\right)}{180 \text{ deg}} \cdot f_{23}(n,t)\right]$$

Sky diffuse illuminance on a tilted surface:

$$E_{ds}(n,t) := E_{dh}(n,t) \cdot \left[\left(1 - F_1(n,t)\right) \cdot \left(\frac{1 + \cos\left(\beta_w\right)}{2}\right) + F_1(n,t) \cdot \frac{a_p(n,t)}{b_p(n,t)} + F_2(n,t) \cdot \sin\left(\beta_w\right) \right]$$

Ground-reflected illuminance on a tilted surface:

 $E_{dg}(n,t) := E_{h}(n,t) \cdot \rho_{g}(n,t) \cdot \frac{1 - \cos(\beta_{W})}{2}$

Total diffuse illuminance on a tilted surface:

 $\mathrm{E}_{\mathrm{d}}(n,t) := \mathrm{E}_{\mathrm{ds}}(n,t) + \mathrm{E}_{\mathrm{dg}}(n,t)$

The total incident illuminance on a tilted surface:

 $\mathbf{E}(\mathbf{n},t) := \mathbf{E}_{\mathbf{b}}(\mathbf{n},t) + \mathbf{E}_{\mathbf{ds}}(\mathbf{n},t) + \mathbf{E}_{\mathbf{dg}}(\mathbf{n},t)$



Illuminance on facade surface for n=188 (July, 7th) (Summer example)

Illuminance on facade surface for n=20 (Jan, 20th) (Winter example)



Switch from function of time to time array: Solar Illuminance:

$$E_{b_{t,n}} := E_b(n,t)$$
 $E_{ds_{t,n}} := E_{ds}(n,t)$ $E_{dg_{t,n}} := E_{dg}(n,t)$ $E_{d_{t,n}} := E_d(n,t)$ $E_{t,n} := E(n,t)$
150

Direct sunlight cut-off angle:



Detail of the louver profile



Measured blind cut-off angle vs. sunlight profile angle

From the trendline in the upper graph:

$$\Omega_{\text{cutoff}}(n,t) := \left(1.8299 \frac{\lambda(n,t)}{\text{deg}} - 67.343\right) \text{deg}$$



Profile angle of direct sunlight for Jan 20th and its corresponding cut-off angle:

 $Profile(n,t) := temp1(n,t) \cdot Interval_{angle}$



...Round down the profile angle to the closest feasible angle...

Measured visible transmittance of the window

* Data for Bright-dip anodized louver is used here

1. Measured visible transmittance under clear sky condition

÷	(-95	90	75	60	45	30	15	0
	-90	0	0	0	0	0	0	0
	-75	3.717445	0.197449	0.748431	0.541901	1.373018	1.490288	2.028231
	-60	14.56017	6.41723	3.86281	3.480992	5.852101	7.692300	12.026
	-45	26.00719	12.61798	8.59240	8.42052	14.69012	21.50193	29.3242
	-30	31.7701	16.18974	11.06989	17.25202	34.50161	41.30402	41.05009
	-15	35.80079	18.62646	20.31486	36.70375	38.67756	56.83688	47.15042
clear ·=	0	37.41398	19.86209	29.24623	41.51505	50.67307	63.76319	59.04157
	15	36.33416	19.19833	31.36084	38.03574	61.98619	69.4151	50.58728
	30	32.61867	17.2836	36.68873	38.98086	65.90815	67.5290	40.22766
	45	25.7475	14.10295	34.37291	48.39840	60.0552	56.40419	33.6329
	60	17.35069	8.99302	50.88821	32.31197	42.89877	33.3167	16.40732
	75	4.44736	2.402579	19.45839	13.01872	5.537123	6.268169	2.41447
	90	0	0	0	0	0	0	0)

 $\text{Tilt}_{\text{clear}} \coloneqq \tau_{\text{clear}}^{\langle 1 \rangle}$

 $Profile_{clear} := \left(\tau_{clear}^{T}\right)^{\langle l \rangle}$

...The first column of the matrix shows the direct sunlight profile angle

... The first row of the matrix is the blind tilt angle

2. Measured effective transmittance under overcast sky condition

	(-90	0	
	-75	0.880796	
	-60	9.082922	
	-45	19.19018	
	-30	26.10011	
	-15	36.16568	
$\tau_{overcast} :=$	0	43.2547	
	15	46.4809	
	30	43.26672	
	45	34.99687	
	60	21.85089	
	75	4.786902	
	90	0)	

$$Tilt_{overcast} := \tau_{overcast}$$
 ... The first column of the matrix shows the direct sunlight profile angle

$$Profile_{overcast} := \left(\tau_{overcast}^{T}\right)^{\langle 1 \rangle}$$

... The first row of the matrix is the blind tilt angle

A simplified control strategy

1. Blind control optimized for maximum view to exterior

$$temp(n,t) := floor\left(\frac{\Omega_{cutoff}(n,t)}{Interval_{angle}}\right)$$

 $max_view(n,t) := \begin{cases} data \leftarrow 0 & \text{if } temp(n,t) > 0 \\ data \leftarrow temp(n,t) & \text{otherwise} \\ data \end{cases}$

 $\Omega_{\max_view}(n,t) := \max_view(n,t) \cdot \text{Interval}_{angle}$

...Blind tilt angle optimized for maximum view to exterior

Ω _{max_}	$view^{(20,t)}$
-75	∙deg
-60	
-45	
-30	
-30	
-30	
-30	
-30	
-45	
-60	-
-75	

2. Blind control optimized for maximum effective transmittance in clear sky condition

$$\begin{aligned} \tau_{\max_tran}(n,t) &\coloneqq & \text{value1}(n,t) \leftarrow 0 \\ \text{for } jj \in -6.. \ \text{temp}(n,t) \\ & \quad \left| \begin{array}{c} \text{col}(n,t) \leftarrow \left| \text{match} \left(\frac{\text{Profile}(n,t)}{\text{deg}}, \text{Profile}_{\text{clear}} \right) \right| \\ & \quad \text{row}(n,t) \leftarrow \left| \text{match} \left(\frac{jj \cdot \text{Interval}_{angle}}{\text{deg}}, \text{Tilt}_{clear} \right) \right| \\ & \quad \text{ss1}(n,t) \leftarrow \tau_{clear}_{row}(n,t), \ \text{col}(n,t) \\ & \quad \text{value1}(n,t) \leftarrow \text{ss1}(n,t) \quad \text{if } \ \text{ss1}(n,t) > \text{value1}(n,t) \\ & \quad \text{value1}(n,t) \end{aligned}$$

$$row_{max tran}(n,t) := value2(n,t) \leftarrow 0$$

for
$$jj \in -6..$$
 temp (n, t)

$$\begin{vmatrix} coll(n, t) \leftarrow & \left| match\left(\frac{Profile(n, t)}{deg}, Profile_{clear}\right) \right| \\
rowl(n, t) \leftarrow & \left| match\left(\frac{jj \cdot Interval_{angle}}{deg}, Tilt_{clear}\right) \right| \\
ss2(n, t) \leftarrow \tau_{clear_{rowl}(n, t), coll(n, t)} \\
ss3(n, t) \leftarrow rowl(n, t) \quad \text{if } ss2(n, t) > value2(n, t) \\
value2(n, t) \leftarrow ss2(n, t) \quad \text{if } ss2(n, t) > value2(n, t) \\
ss3(n, t) \leftarrow ss3(n, t) = value2(n, t) \\
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ss3(n, t) \leftarrow ss3(n,$$

 $\Omega_{max_tran}(n,t) := row_{max_tran}(n,t) \cdot Interval_{angle} - 120deg$

Ω _{max_}	tran ^(20, t)
-75	∙deg
-60	
-45	
-30	
-30	
-30	
-30	
-30	
-45	
-60	
-75	

...Blind tilt angle optimized for maximum effective transmittance under clear sky condition

<u>Calculate blind tilt angles for Top and Middle sections of the facade based on</u> <u>selected control strategy:</u>

1. Top section (optimized for maximum transmittance)

$$\Omega_{top}(n,t) := \begin{vmatrix} 0 \text{deg} & \text{if } I_{d_{t,n}} \leq \text{limit} \\ \Omega_{max_tran}(n,t) & \text{if } I_{d_{t,n}} > \text{limit} \end{vmatrix}$$

$$\operatorname{col}(n,t) := \left| \operatorname{match} \left(\frac{\operatorname{Profile}(n,t)}{\operatorname{deg}}, \operatorname{Profile}_{\operatorname{clear}} \right) \right|$$

$$\operatorname{row}(n,t) := \left| \operatorname{match}\left(\frac{\Omega_{\operatorname{top}}(n,t)}{\operatorname{deg}}, \operatorname{Tilt}_{\operatorname{clear}} \right) \right|$$

 $\tau_{top}(n,t) := \begin{cases} \frac{\tau_{overcast}_{row(n,t),2}}{100} & \text{if } l_{d_{t,n}} \le \text{limit} \\ \frac{\tau_{clear}_{row(n,t),col(n,t)}}{100} & \text{if } l_{d_{t,n}} > \text{limit} \end{cases}$

$\Omega_{ton}(n,t) =$	
l deg	$\tau_{top}(n,t) =$
	0.465
	0.465
0	0.465
0	0.465
0	0.465
0	0.465
0	0.465
0	0.105
0	0.465
0	0.465
	0.465
	0.465
0	0.465
0	0.465
0	0.465
0	0.465

... control of the top section is optimized for the maximum transmittance

2. Middle section (optimized for maximum view to exterior)

$$\begin{split} \Omega_{mid}(n,t) &\coloneqq \left| \begin{array}{l} 0 \text{deg} \quad \text{if } I_{d_{t,n}} \leq \text{limit} \\ \Omega_{max_view}(n,t) \quad \text{if } I_{d_{t,n}} > \text{limit} \end{array} \right| \\ \text{coll}(n,t) &\coloneqq \left| \text{match} \left(\frac{\text{Profile}(n,t)}{\text{deg}}, \text{Profile}_{\text{clear}} \right) \right| \\ \text{rowl}(n,t) &\coloneqq \left| \text{match} \left(\frac{\Omega_{mid}(n,t)}{\text{deg}}, \text{Tilt}_{\text{clear}} \right) \right| \\ \tau_{mid}(n,t) &\coloneqq \left| \frac{\tau_{\text{overcast}}}{100} \quad \text{if } I_{d_{t,n}} \leq \text{limit} \\ \frac{\tau_{\text{clear}}}{100} \quad \text{if } I_{d_{t,n}} > \text{limit} \right| \\ \end{split}$$

... control of the top section is optimized for the maximum transmittance

$\Omega_{mid}^{(i)}$	n,t) =	τ. (nt)	=
0	·deg		
0		0.405	
0		0.405	
0		0.465	
0		0.465	
		0.465	
		0.465	
	<i></i>	0.465	
0		0.465	
0		0.465	
0		0.465	
0		0.465	
0		0.465	
0		0.465	
0		0.105	
0		0.403	
		0.465	
	l		1

View Factors of Room Surfaces



Legend

1: South facade (2+3+4)

2. Top section of facade

3. Middle section of facade

4. spandrel section

5. Floor 6. North Wall 9. East wall

- 7. Ceiling
- 8. West wall

The view factors for the room below are determined after calculating first the view factors between two rectangular finite surfaces inclined at 90 degrees to each other with one common surface as follows:



Define the following intermediate variables for calculating view factor from surface i to surface j:

$$w = \frac{w1}{comm} \qquad h = \frac{h2}{comm}$$

$$A(h,w) := h^{2} + w^{2} \qquad B(w) := 1 + w^{2}$$

$$C(h) := 1 + h^{2} \qquad D(h,w) := 1 + (h^{2} + w^{2})$$

$$E(w) := w^{2} \qquad G(h) := h^{2}$$

View factor Fij from i to j:

$$\operatorname{Fij}(w,h) := \frac{\left(w \cdot \operatorname{atan}\left(\frac{1}{w}\right) + h \cdot \operatorname{atan}\left(\frac{1}{h}\right)\right) - \sqrt{A(h,w)} \cdot \operatorname{atan}\left(\frac{1}{\sqrt{A(h,w)}}\right) \dots}{\pi \cdot w}$$

Area of room surfaces:

$A_1 := W_{rm} \cdot H_{rm}$	$A_4 := H_{sp} \cdot W_{rm}$	$A_7 := D_{rm} \cdot W_{rm}$
$A_2 := W_{glass} \cdot H_{top}$	$A_5 := D_{rm} \cdot W_{rm}$	$A_8 := H_{rm} \cdot D_{rm}$
$A_3 := W_{glass} \cdot H_{mid}$	$A_6 := W_{rm} H_{rm}$	$A_9 := H_{rm} \cdot D_{rm}$

View Factors of Between Surface 5 and Surface 6:

Calculate view factors:

w1 :=
$$D_{rm}$$
 h2 := H_{rm} comm := W_{rm}
w := $\frac{w1}{comm}$ h := $\frac{h2}{comm}$
F₅₆

$$F_{56} := Fij(w, h)$$
 $F_{65} := A_5 \cdot \frac{F_{56}}{A_6}$
 Surface 6

 $F_{76} := F_{56}$
 $F_{67} := F_{65}$
 Surface 6

 $F_{51} := F_{56}$
 $F_{15} := F_{65}$
 Surface 5

 $F_{17} := F_{15}$
 $F_{71} := F_{51}$
 Surface 5

View Factors of Between Surface 5 and Surface 8:

w1 := W m
 h2 := H m
 comm := D m

 w :=
$$\frac{w1}{comm}$$
 h := $\frac{h2}{comm}$

 F₅₈ := Fij(w, h)
 F₈₅ := A₅. $\frac{F_{58}}{A_8}$

 F₅₉ := F₅₈
 F₉₅ := F₈₅

 F₇₈ := F₅₈
 F₈₇ := F₈₅

 F₇₉ := F₅₉
 F₉₇ := F₈₇

View Factors of Between Surface 5 and Surface 7:

$$F_{57} := 1 - F_{51} - F_{56} - F_{58} - F_{59}$$

View Factors of Between Surface 6 and Surface 8:

w1 := W
rmh2 := D
rmcomm := H
rmw :=
$$\frac{w1}{comm}$$
h := $\frac{h2}{comm}$ F68 := Fij(w,h)F86 := A6 $\frac{F_{68}}{A_8}$ F69 := F68F96 := F86F81 := F86F18 := A8 $\frac{F_{81}}{A_1}$ Surface 6w1

View Factors of Between Surface 6 and Surface 1:

$$F_{61} := 1 - F_{65} - F_{67} - F_{68} - F_{69}$$

 $F_{16} := F_{61}$



View Factors of Between Surface 8 and Surface 9:

 $F_{89} := 1 - F_{81} - F_{85} - F_{86} - F_{87}$

 $F_{98} := F_{89}$

Surface 9	
Surface 8	/



View factors between surfaces 2, 3 and surface 5.

$$\begin{split} & Fb_3 a := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{top} + H_{mid} + H_{sp} \quad comm := W_{glass} \\ & w := \frac{wl}{comm} & h := \frac{h2}{comm} \\ & Fb_3 2 c := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{sp} \quad comm := W_a \\ & w := \frac{wl}{comm} & h := \frac{h2}{comm} \\ & Fa_2 c := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{mid} + H_{sp} \quad comm := W_a \\ & w := \frac{wl}{comm} & h := \frac{h2}{comm} \\ & Fa_2 c := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{top} + H_{mid} + H_{sp} \quad comm := W_a \\ & w := \frac{wl}{comm} & h := \frac{h2}{comm} \\ & Fa_2 c := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{top} + H_{mid} + H_{sp} \quad comm := W_a \\ & w := \frac{wl}{comm} & h := \frac{h2}{comm} \\ & Fa_2 c : c := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h := \frac{h2}{comm} \\ & Fa_2 c : c := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h := \frac{h2}{comm} \\ & Fa_2 c : c := Fij(w, h) \\ & w1 := D_{rm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_a \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{glass} + W_{sp} \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{sp} \\ & w := \frac{wl}{comm} & h2 := H_{mid} + H_{sp} \quad comm := W_{sp} \\ &$$
$$Fab_c1c2e3 := Fij(w, h)$$

w1 :=
$$D_{rm}$$

$$h2 := H_{top} + H_{mid} + H_{sp}$$
 comm := $W_{glass} + W_{a}$

$$w := \frac{wl}{comm}$$
 $h := \frac{h2}{comm}$

 $Fab_c1c2c3e32 := Fij(w,h)$

$$F3_b := (Fb_3e - Fb_e) \cdot \frac{Ab}{A_3}$$

$$F2_b := (Fb_32e - Fb_3e) \cdot \frac{Ab}{A_2}$$

$$Fa_3e := \frac{Aab \cdot Fab_c 1c2e3 - Aa \cdot Fa_c 1c2 - Ab \cdot Fb_3e}{2 \cdot Aa}$$

$$Fa_32e := \frac{Aab \cdot Fab_c 1c2c3e32 - Aa \cdot Fa_c 1c2c3 - Ab \cdot Fb_32e}{2 \cdot Aa}$$

$$Fa_e := \frac{Aab \cdot Fab_c 2e - Aa \cdot Fa_c 2 - Ab \cdot Fb_e}{2 \cdot Aa}$$

$$F3_e a := (Fa_b 3e - Fa_b) \cdot \frac{Aa}{a}$$

F2_a := (Fa_32e - Fa_3e)
$$\frac{Aa}{A_2}$$

$$F_{35} := 2 \cdot F_3 a + F_3 b$$
 $F_{53} := A_3 \cdot \frac{F_{35}}{A_5}$

$$F_{25} := 2 \cdot F_{2a} + F_{2b}$$
 $F_{52} := A_2 \cdot \frac{F_{25}}{A_5}$

View factors between surfaces 2, 3 and surface 7.



 $Fb_2d := Fij(w, h)$

$$w1 := D_{rm} \qquad h2 := H_{mid} + H_{facadetop} + H_{top} \qquad comm := W_{glass}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fb_{3}2d := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{facadetop} \qquad comm := W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fa_{c}c4 := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{facadetop} + H_{top} \qquad comm := W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fa_{c}c3c4 := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{mid} + H_{facadetop} + H_{top} \qquad comm := W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fa_{c}c1c3c4 := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{mid} + H_{facadetop} + H_{top} \qquad comm := W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fa_{c}c1c3c4 := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{facadetop} \qquad comm := W_{glass} + W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fa_{c}c4d := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{facadetop} + H_{top} \qquad comm := W_{glass} + W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fa_{c}c1c3c4 := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{facadetop} \qquad comm := W_{glass} + W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

$$Fa_{c}c1c3c4 := Fij(w, h)$$

$$w1 := D_{rm} \qquad h2 := H_{facadetop} \qquad comm := W_{glass} + W_{a}$$

$$w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$$

 $Fab_2c3c4d := Fij(w, h)$

w1 :=
$$D_{rm}$$

$$h2 := H_{mid} + H_{facadetop} + H_{top}$$
 comm := $W_{glass} + W_{a}$

$$w := \frac{w1}{comm}$$
 $h := \frac{h2}{comm}$

 $Fab_{32c1c3c4d} := Fij(w, h)$

$$F2_b := (Fb_2d - Fb_d) \cdot \frac{Ab}{A_2}$$
$$F3_b := (Fb_32d - Fb_2d) \cdot \frac{Ab}{A_3}$$

$$Fa_2d := \frac{Aab \cdot Fab_2c3c4d - Aa \cdot Fa_c3c4 - Ab \cdot Fb_2d}{2 \cdot Aa}$$

 $Fa_{32d} := \frac{Aab \cdot Fab_{32c1c3c4d} - Aa \cdot Fa_{c1c3c4} - Ab \cdot Fb_{32d}}{2 \cdot Aa}$

$$Fa_d := \frac{Aab \cdot Fab_c 4d - Aa \cdot Fa_c 4 - Ab \cdot Fb_d}{2 \cdot Aa}$$
$$F2_a := (Fa_2 d - Fa_d) \cdot \frac{Aa}{A_2}$$

$$F3_a := (Fa_32d - Fa_2d) \cdot \frac{Aa}{A_3}$$

$$F_{37} := 2 \cdot F_3 = F_3 = F_3$$

$$F_{27} := 2 \cdot F_2 = 4 + F_2 = b$$
 $F_{72} := A_2 \cdot \frac{F_{27}}{A_7}$

View factors between surfaces 2, 3 and surfaces 8, 9.



Ad := $W_{glass} \cdot H_{facadetop}$ Ae := $W_{glass} \cdot H_{sp}$ Ag := $D_{rm} \cdot H_{mid}$ Af := $H_{sp} \cdot D_{rm}$ Ac1 := $H_{mid} W_a$ Ac2 := $H_{sp} \cdot W_a$ Ah := $H_{facadetop} \cdot D_{rm}$ Ac3 := $W_a \cdot H_{top}$

Agf := Ag + Af $Aq := D_{rm} H_{top}$ Aqh := Aq + Ah

 $Aqgh := Aq + Ag + Ah \qquad Aqgf := Ag + Af + Aq \qquad Aqg := Ag + Aq$

w1 :=
$$D_{rm}$$

w := $\frac{w1}{comm}$
 $h2 := W_{glass} + W_{a}$
 $h := \frac{h2}{comm}$

 $Fg_3c1 := Fij(w,h)$

$$w1 := D_{rm}$$
 $h2 := W_{glass} + W_a$ $comm := H_{top}$

$$\begin{split} w &:= \frac{w1}{comm} \qquad h := \frac{h2}{comm} \\ Fq_2c3 &:= Fij(w, h) \\ w1 &:= D_{TR} \qquad h2 := W_a \qquad comm := H_{mid} \\ w &:= \frac{w1}{comm} \qquad h := \frac{h2}{comm} \\ Fg_c1 &:= Fij(w, h) \\ w1 &:= D_{TR} \qquad h2 := W_a \qquad comm := H_{top} \\ w &:= \frac{w1}{comm} \qquad h := \frac{h2}{comm} \\ Fq_c3 &:= Fij(w, h) \\ w1 &:= D_{TR} \qquad h2 := W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h := \frac{h2}{comm} \\ Fh_c4 &:= Fij(w, h) \\ w1 &:= D_{TR} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h := \frac{h2}{comm} \\ Fh_cd4 &:= Fij(w, h) \\ w1 &:= D_{TR} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass} + W_a \qquad comm := H_{facadetop} \\ w &:= \frac{w1}{comm} \qquad h2 := W_{glass}$$

 $comm := H_{facade} + H_{facadetop}$ $h2 := W_{glass} + W_{a}$

$$w := \frac{w1}{comm}$$
 $h := \frac{h2}{comm}$

 $Fqgh_c1c3c4d32 := Fij(w, h)$

w1 := D_{rm}

 $h2 := W_a$

 $h2 := W_a$

 $comm := H_{top} + H_{facadetop}$

 $comm := H_{facade} + H_{facadetop}$

comm := H_{facade}

$$w := \frac{w1}{comm}$$
 $h := \frac{h2}{comm}$

 $Fqh_c3c4 := Fij(w, h)$

$$w1 := D_{rm}$$

$$w := \frac{w1}{comm}$$
 $h := \frac{h2}{comm}$

 $Fqhg_c1c3c4 := Fij(w, h)$

 $w1 := D_{rm}$ $h2 := W_{glass} + W_{a}$

 $w := \frac{wl}{comm}$ $h := \frac{h2}{comm}$

 $Fqg_32c1c3 := Fij(w, h)$

w1 :=
$$D_{rm}$$
 h2 := W_a comm := H_{mid}
w := $\frac{w1}{comm}$ h := $\frac{h2}{comm}$

 $Fg_c1 := Fij(w,h)$

$$F3_g := (Fg_3c1 - Fg_c1) \cdot \frac{Ag}{A_3}$$

$$F2_q := (Fq_2c_3 - Fq_c_3) \cdot \frac{Aq}{A_2}$$

$$Fh_2c_3 := \frac{Aqh \cdot Fqh_c_3c_4d_2 - Ah \cdot Fh_dc_4 - Aq \cdot Fq_2c_3}{2 \cdot Ah}$$

$$Fh_c3 := \frac{Aqh \cdot Fqh_c3c4 - Ah \cdot Fh_c4 - Aq \cdot Fq_c3}{2 \cdot Ah}$$

 $Fhq_3c1 := \frac{Aqgh \cdot Fqgh_c1c3c4d32 - Aqh \cdot Fqh_c3c4d2 - Ag \cdot Fg_3c1}{2 \cdot Aqh}$

$$Fqh_c1 := \frac{Aqgh \cdot Fqhg_c1c3c4 - Aqh \cdot Fqh_c3c4 - Ag \cdot Fg_c1}{2 \cdot Aqh}$$

$$F2_h := (Fh_2c3 - Fh_c3) \cdot \frac{Ah}{A_2}$$

$$F3_qh := (Fhq_3c1 - Fqh_c1) \cdot \frac{Aqh}{A_3}$$

 $h2 := W_a$ $comm := H_{sp}$ wl := D_{rm} $h := \frac{h2}{comm}$ $w := \frac{w1}{comm}$ $Ff_c2 := Fij(w, h)$ $h2 := W_{glass} + W_{a}$ wl := D_{rm} $comm := H_{sp}$ $h := \frac{h2}{comm}$ $w := \frac{w1}{comm}$ $Ff_ec2 := Fij(w,h)$ $wl := D_{rm}$ $h2 := W_{glass} + W_{a}$ $comm := H_{mid} + H_{sp}$ $w := \frac{w1}{comm}$ $h := \frac{h2}{comm}$ $Fgf_c1c2e3 := Fij(w, h)$ $comm := H_{facade} + H_{sp}$ w1 := D $h2 := W_{a1a}$

$$w := \frac{wl}{comm} \qquad h := \frac{h2}{comm}$$

 $Fqgf_c1c2c3e32 := Fij(w, h)$

w1 :=
$$D_{rm}$$
 h2 := W_a comm := $H_{mid} + H_{sp}$
w := $\frac{w1}{comm}$ h := $\frac{h2}{comm}$

$$Fgf_clc2 := Fij(w,h)$$

w1 :=
$$D_{rm}$$
 h2 := W_a comm := $H_{facade} + H_{sp}$

$$w := \frac{wl}{comm}$$
 $h := \frac{h2}{comm}$

$$Fqgf_clc2c3 := Fij(w,h)$$

$$Ff_3c1 := \frac{Agf \cdot Fgf_c1c2e3 - Af \cdot Ff_ec2 - Ag \cdot Fg_3c1}{2 \cdot Af}$$

$$Ff_c1 := \frac{Agf \cdot Fgf_c1c2 - Af \cdot Ff_c2 - Ag \cdot Fg_c1}{2 \cdot Af}$$

$$F3_f := (Ff_3c1 - Ff_c1) \cdot \frac{Af}{A_3}$$

$$Ffg_2c3 := \frac{Aqgf \cdot Fqgf_c1c2c3e32 - Agf \cdot Fgf_c1c2e3 - Aq \cdot Fq_2c3}{2 \cdot Agf}$$

$$Ffg_c3 := \frac{Aqgf \cdot Fqgf_c1c2c3 - Agf \cdot Fgf_c1c2 - Aq \cdot Fq_c3}{2 \cdot Agf}$$

$$F2_fg := (Ffg_2c3 - Ffg_c3) \cdot \frac{Agf}{A_2}$$

$$F_{39} := F3_qh + F3_g + F3_f$$

$$F_{93} := A_3 \cdot \frac{F_{39}}{A_9}$$

$$F_{38} := F_{39}$$

$$F_{83} := F_{93}$$

$$F_{91} := F_{81}$$

$$F_{19} := A_9 \cdot \frac{F_{91}}{A_1}$$

$$F_{36} := 1 - 2 \cdot F_{39} - 2F_{37}$$

$$F_{63} := F_{36} \cdot \frac{A_3}{A_6}$$

$$F_{29} := F2_h + F2_q + F2_fg$$
 $F_{92} := F_{29} \cdot \frac{A_2}{A_9}$ $F_{28} := F_{29}$ $F_{82} := F_{92}$ $F_{26} := 1 - 2 \cdot F_{29} - F_{27} - F_{25}$ $F_{62} := F_{26} \cdot \frac{A_2}{A_6}$ $F_{74} := F_{71} - F_{72} - F_{73}$ $F_{54} := F_{51} - F_{53} - F_{52}$ $F_{94} := F_{91} - F_{93} - F_{92}$ $F_{84} := F_{81} - F_{83} - F_{82}$ $F_{64} := F_{61} - F_{63} - F_{62}$ $F_{24} := 0$

$$F_{47} := A_7 \frac{F_{74}}{A_4} \qquad F_{46} := A_6 \frac{F_{64}}{A_4} \qquad F_{48} := A_8 \frac{F_{84}}{A_4}$$

$$F_{49} := A_9 \frac{F_{94}}{A_4} \qquad F_{45} := A_5 \frac{F_{54}}{A_4}$$

More on View factors

$$F_{11} := 0$$
 $F_{44} := 0$ $F_{77} := 0$ $F_{22} := 0$ $F_{55} := 0$ $F_{88} := 0$ $F_{33} := 0$ $F_{66} := 0$ $F_{99} := 0$ $F_{12} := 0$ $F_{13} := 0$ $F_{14} := 0$ $F_{17} := F_{15}$ $F_{21} := 0$ $F_{23} := 0$ $F_{31} := 0$ $F_{32} := 0$ $F_{34} := 0$ $F_{41} := 0$ $F_{42} := 0$ $F_{43} := 0$

In Summary

$F_{11} = 0$ $F_{12} = 0$ $F_{13} = 0$		$F_{21} = 0$			$F_{41} = 0$			
		$F_{22} = 0$	$F_{32} = 0$			$F_{42} = 0$		
		$F_{23} = 0$	$F_{33} = 0$			$F_{43} = 0$		
	$F_{14} = 0$	$F_{24} = 0$		$F_{34} = 0$		$F_{44} = 0$		
$F_{15} = 0.233$ $F_{16} = 0.069$ $F_{17} = 0.233$ $F_{18} = 0.233$ $F_{19} = 0.233$		$F_{25} = 0.148$	$F_{35} = 0.234$ $F_{36} = 0.112$ $F_{37} = 0.193$ $F_{38} = 0.251$ $F_{39} = 0.251$			$F_{45} = 0.428$ $F_{46} = 0.047$ $F_{47} = 0.273$ $F_{48} = 0.311$ $F_{49} = 0.311$		
		$F_{26} = 0.069$,			
		$F_{27} = 0.321$			i			
		$F_{28} = 0.231$						
		$F_{29} = 0.231$						
F5	1 = 0.116	$F_{61} = 0.069$	$F_{71} = 0.11$	16	$F_{81} = 0.11$	6	$F_{91} = 0.116$	
F ₅₂	2 = 0.023	$F_{62} = 0.021$	$F_{72} = 0.05$	5	$F_{82} = 0.03$	6	$F_{92} = 0.036$	
F ₅₃	$_{3} = 0.036$	$F_{63} = 0.035$	$F_{73} = 0.03$	3	$F_{83} = 0.03$	9	$F_{93} = 0.039$	
F ₅₄	4 = 0.057	$F_{64} = 0.012$	$F_{74} = 0.03$	36	$F_{84} = 0.04$	1	$F_{94} = 0.041$	
$F_{55} = 0$		$F_{65} = 0.233$	$F_{75} = 0.286$		$F_{85} = 0.241$		$F_{95} = 0.241$	
F50	₆ = 0.116	$F_{66} = 0$	$F_{76} = 0.11$	16	$F_{86} = 0.11$	6	$F_{96} = 0.116$	
$F_{57} = 0.286$		$F_{67} = 0.233$	$F_{77} = 0$		$F_{87} = 0.241$		$F_{97} = 0.241$	
$F_{58} = 0.241$		$F_{68} = 0.233$	$F_{78} = 0.241$		$F_{88} = 0$		$F_{98} = 0.286$	
$F_{59} = 0.241$		$F_{69} = 0.233$	$F_{79} = 0.241$		$F_{89} = 0.286$		$F_{99} = 0$	

$$F := \begin{pmatrix} F_{22} & F_{23} & F_{24} & F_{25} & F_{26} & F_{27} & F_{28} & F_{29} \\ F_{32} & F_{33} & F_{34} & F_{35} & F_{36} & F_{37} & F_{38} & F_{39} \\ F_{42} & F_{43} & F_{44} & F_{45} & F_{46} & F_{47} & F_{48} & F_{49} \\ F_{52} & F_{53} & F_{54} & F_{55} & F_{56} & F_{57} & F_{58} & F_{59} \\ F_{62} & F_{63} & F_{64} & F_{65} & F_{66} & F_{67} & F_{68} & F_{69} \\ F_{72} & F_{73} & F_{74} & F_{75} & F_{76} & F_{77} & F_{78} & F_{79} \\ F_{82} & F_{83} & F_{84} & F_{85} & F_{86} & F_{87} & F_{88} & F_{89} \\ F_{92} & F_{93} & F_{94} & F_{95} & F_{96} & F_{97} & F_{98} & F_{99} \end{pmatrix}$$

	(0	0	0	0.148	0.069	0.321	0.231	0.231
	0	0	0	0.234	0.112	0.193	0.251	0.251
	0	0	0	0.428	0.047	0.273	0.311	0.311
Б	0.023	0.036	0.057	0	0.116	0.286	0.241	0.241
r =	0.021	0.035	0.012	0.233	0	0.233	0.233	0.233
	0.05	0.03	0.036	0.286	0.116	0	0.241	0.241
	0.036	0.039	0.041	0.241	0.116	0.241	0	0.286
	0.036	0.039	0.041	0.241	0.116	0.241	0.286	0)

Radiosity calculation

i) For diffuse daylighting

$$E_{\text{top}_{t,n}} := E_{t,n} \cdot \tau_{\text{top}}(n,t)$$
$$E_{\text{mid}_{t,n}} := E_{t,n} \cdot \tau_{\text{mid}}(n,t)$$



Initial luminous exitance of each room surface:

Reflectance of each room surface:

1	(p _{top}	0	0	0	0	0	0	0	
ρ:=	0	ρ _{mid}	0	0	0	• 0	0	0	
	0	0	ρ _{sp}	0	0	0	0	0	
	0	0	0	ρ _{floor}	0	0	. 0	0	
	0	0	0	0	ρ_{wall}	0	0	0	
	0	0	0	0	0	^ρ ceiling	0	0	
	0	0	0	0	0	0	ρ_{wall}	0	
	0	0	0	0	0	0	0	Pwall	

"Final" luminous exitance of each room surface:

 $\mathbf{i} := 8 \qquad \mathbf{I} := \text{identity}(8) = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$

$$M_{1_{t,n}} := (1 - \rho \cdot F)^{-1} \cdot M_{o_{t,n}}$$

Configuration factors between room surfaces and workplane

Configuration factors for points positioned to a plane parallel to the source plane:

$$C_{\text{parallel}}(z, y, w) \coloneqq \frac{1}{2\pi} \left(\frac{z}{\sqrt{z^2 + y^2}} \cdot \operatorname{atan}\left(\frac{w}{\sqrt{z^2 + y^2}}\right) + \frac{w}{\sqrt{w^2 + y^2}} \cdot \operatorname{atan}\left(\frac{z}{\sqrt{w^2 + y^2}}\right) \right)$$

Configuration factors for points positioned to a plane perpendicular to the source plane:

$$C_{\text{perpendicular}}(z, y, w) := \frac{1}{2 \cdot \pi} \left(\operatorname{atan}\left(\frac{w}{y}\right) - \frac{y}{\sqrt{z^2 + y^2}} \cdot \operatorname{atan}\left(\frac{w}{\sqrt{z^2 + y^2}}\right) \right)$$

 $N_p := 5$...number of selected points

$$j := 1, 2.. N_p$$

Spandrel section

$$z_{j,t} := if[(H_{sp} - H_{workplane}) > 0m, H_{sp} - H_{workplane}, 0.m] \qquad y_{j,t} := \frac{D_{rm}}{N_p + 1} \cdot j \qquad w_{j,t} := \frac{W_{rm}}{2}$$

$$C_{s4_{j,t}} := 2C_{perpendicular} \left(z_{j,t}^{y}, y_{j,t}^{y}, w_{j,t} \right)$$

Middle section

$$z_{j,t} \coloneqq H_{mid} + H_{sp} - H_{workplane} \qquad y_{j,t} \coloneqq \frac{D_{rm}}{N_p + 1} \cdot j \qquad w_{j,t} \coloneqq \frac{W_{rm}}{2}$$
$$C_{s3_{j,t}} \coloneqq 2C_{perpendicular} \left(z_{j,t}, y_{j,t}, w_{j,t} \right) - C_{s4_{j,t}}$$

Top section

$$z_{j,t} := H_{top} + H_{mid} + H_{sp} - H_{workplane} \qquad y_{j,t} := \frac{D_{rm}}{N_p + 1} \cdot j \qquad w_{j,t} := \frac{W_{rm}}{2}$$

$$C_{s2_{j,t}} := 2C_{perpendicular}(z_{j,t}, y_{j,t}, w_{j,t}) - C_{s3_{j,t}} - C_{s4_{j,t}}$$

The rest of the facade surface

$$z_{j,t} := H_{rm} - H_{workplane} \qquad y_{j,t} := \frac{D_{rm}}{N_{p} + 1} \cdot j \qquad w_{j,t} := \frac{W_{rm}}{2}$$
$$C_{s1_{j,t}} := 2C_{perpendicular} (z_{j,t}, y_{j,t}, w_{j,t}) - C_{s2_{j,t}} - C_{s3_{j,t}} - C_{s4_{j,t}}$$

North wall

$$z_{j,t} \coloneqq H_{rm} - H_{workplane} \qquad y_{j,t} \coloneqq \frac{D_{rm}}{N_p + 1} \cdot \left(N_p + 1 - j\right) \qquad w_{j,t} \coloneqq \frac{W_{rm}}{2}$$
$$C_{s6_{j,t}} \coloneqq 2C_{perpendicular} \left(z_{j,t}, y_{j,t}, w_{j,t}\right)$$

East wall

$$z_{j,t} := H_{rm} - H_{workplane}$$
 $y_{j,t} := \frac{W_{rm}}{2}$ $w_{j,t} := \frac{D_{rm}}{N_p + 1} j$

$$C_{s9a_{j,t}} := C_{perpendicular} \left(z_{j,t}, y_{j,t}, w_{j,t} \right)$$

$$w_{j,t} := \frac{D_{rm}}{N_p + 1} \cdot \left(N_p + 1 - j\right)$$

~

$$C_{s9b_{j,t}} := C_{perpendicular} \left(z_{j,t}^{y}, y_{j,t}^{y}, w_{j,t} \right)$$

$$C_{s9_{j,t}} := C_{s9a_{j,t}} + C_{s9b_{j,t}}$$

West wall (surface 8)

$$z_{j,t} := H_{rm} - H_{workplane} \qquad y_{j,t} := \frac{W_{rm}}{2} \qquad w_{j,t} := \frac{D_{rm}}{N_p + 1} \cdot j$$
$$C_{s8a_{j,t}} := C_{perpendicular} \left(z_{j,t}, y_{j,t}, w_{j,t} \right)$$
$$w_{j,t} := \frac{D_{rm}}{N_p + 1} \cdot \left(N_p + 1 - j \right)$$

$$C_{s8b_{j,t}} := C_{perpendicular} \left(z_{j,t}, y_{j,t}, w_{j,t} \right)$$

 $C_{s8_{j,t}} := C_{s8a_{j,t}} + C_{s8b_{j,t}}$

Floor (surface 5)

 $C_{s5}_{j,t} := 0$... surface below the measuring points

Ceiling (surface 7)

 $C_{s7_{j,t}} := 1 - C_{s1_{j,t}} - C_{s2_{j,t}} - C_{s3_{j,t}} - C_{s4_{j,t}} - C_{s6_{j,t}} - C_{s8_{j,t}} - C_{s9_{j,t}}$

In Summary

 $C_{room_{j,t}} := \begin{pmatrix} C_{s2_{j,t}} & C_{s3_{j,t}} & C_{s4_{j,t}} & C_{s5_{j,t}} & C_{s6_{j,t}} & C_{s7_{j,t}} & C_{s8_{j,t}} & C_{s9_{j,t}} \end{pmatrix}$

Final Workplane Illuminance due to daylighting

 $Point(j,t,n) := C_{room_{j,t}} \cdot M_{l_{t,n}}$

...workplane illuminace due to diffuse daylighting transmitted through the fenestration

$$E_{wp_{t,n}} := (Point(1,t,n) Point(2,t,n) Point(3,t,n) Point(4,t,n) Point(5,t,n))$$

Workplane illuminance distribution alone the center line of the room on n=188 (July, 7th) at 12pm (noon) (Summer example) (intermediate sky conditions)

