December 2014

Subdivided Windows with Mixed Shading Devices: A Daylighting Solution for Effective Integration of Occupants into the Building Environmental Control

Leyla Sanati
University of Wisconsin-Milwaukee

SUBDIVIDED WINDOWS WITH MIXED SHADING DEVICES:

A DAYLIGHTING SOLUTION FOR EFFECTIVE INTEGRATION OF OCCUPANTS

INTO THE BUILDING ENVIRONMENTAL CONTROL

by

Leyla Sanati

A Dissertation Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

in Architecture

at

The University of Wisconsin-Milwaukee

December 2014

ABSTRACT

SUBDIVIDED WINDOWS WITH MIXED SHADING DEVICES:
A DAYLIGHTING SOLUTION FOR EFFECTIVE INTEGRATION OF OCCUPANTS INTO THE BUILDING ENVIRONMENTAL CONTROL

by

Leyla Sanati

The University of Wisconsin-Milwaukee, 2014
Under the Supervision of Professor D. Michael Utzinger

Daylighting is one of the most challenging aspects of an ecological building design. The dynamic nature of daylight along with a wide range of individual preferences makes it a complex design issue. The art of daylighting relies on fine-tuning a delicate balance between admitting sufficient daylight for occupant well being and task performance and preventing glare and over heating. These goals are rarely achieved in buildings where fenestration design is reduced to an opening with an interior blind due to occupants' infrequent shade operation. To address this problem, a number of automatic shading devices have been developed to be integrated with the lighting control system for an optimized daylit environment. Although such systems reveal substantial energy savings in laboratory and energy modeling tools, evidence has accumulated that they do not perform well in real buildings and disregard occupants' need for perceived control over their environment. This dissertation aimed at examining the potentials of a subdivided window in solving the current challenges of daylighting side-lit spaces. The field observation suggested that a subdivided window with horizontal shading devices increases occupants' chance of raising the blinds and reduces their lighting energy consumption. The simulation studies established that subdivided windows combining automatic and manual shading devices have the potential to significantly reduce the lighting energy use and maintain a well-daylit environment throughout the year.

To my Dear Parents

I couldn't be here without you.

TABLE OF CONTENTS

CHAPTER 4: Daylight Performance Metrics

CHAPTER 5: Design Options for Subdivided Windows

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I was able to complete this dissertation with encouragement, assistance, and support from many wonderful mentors, friends, and family members. First of all, I would like to thank my advisor, Professor Michael Utzinger for his patience, support, thoughtful suggestions, and words of hope and encouragement. I am grateful to members of my committee, Professors James Wasley, Gerald Weisman, Brian Schermer, and Filip Tejchman as well as other academic mentors at UWM for their guidance and support of my dissertation work. I would like to express my gratitude to Mr. Dennis Manely and his assistants for their invaluable help in preparation and installation of the subdivided window shading devices and the UWM School of Architecture and Urban Planning students who participated in my research.

The annual daylight simulations in this dissertation would not be possible without Radiance tools and associated analysis methods developed by Greg Ward. I am also grateful for his guidance and his patience in answering my questions. I have received invaluable assistance from radiance experts and mailing list members, Andy McNeil, Axel Jacobs, Rob Guglielmetti, Jack de Valpine, Germán Larrain, and Thomas Bleicher. I am indebted to Kevin Van Den Wymelenberg and Christoph Reinhart for providing valuable information on HDR imaging, and to Jan Wienold for developing Evalglare.

Last but not least, I would like to acknowledge support from my family: thanks to my beloved parents, Jafar Sanati and Effat Mashayekhi, for their love, support, and sacrifice throughout my life, to my dear husband Kourosh for his love and patience, to my lovely daughter Keemia for bringing joy to my life, and to my brothers Amin, Mehdi, Saeed and Youssef for their continued encouragement.

CHAPTER 1
Introduction

1.1. THE BENEFITS OF DAYLIGHTING BUILDINGS

The admission of daylight into the buildings has numerous benefits concerning building energy efficiency, occupant mood, well being, and productivity, and aesthetics. The energy saving potential of daylighting has long been of interest for the building community, and empirical studies show that utilization of daylight in buildings can reduce lighting energy consumption (Lee et al., 1998). However, the design community is increasingly shifting its attention toward occupants' comfort and health in regards to daylighting (Reinhart & Selkowitz, 2006). Various physiological and psychological benefits have been attributed to the presence of daylight in buildings.

The physiological aspect of daylighting is related to its influence on human brain and visual system. Daylight through the medium of retinal ganglion cells triggers an area of human brain, known as suprachiasmatic nucleus (SCN), which is responsible for driving daily wake–sleep cycles as well as certain hormonal levels (Berson, Dunn, & Takao, 2002; as cited in Reinhart & Selkowitz, 2006). In fact, daylight helps us synchronize our internal clock to 24 hours, thus our natural bodily functions match the rhythm of life.

Recent studies have looked at the spectral composition and intensity of light required to send signals to the SCN and concluded that the required light levels for human physiological needs are higher than the minimum visual task requirements (Reinhart & Selkowitz, 2006). Daylight can provide this high intensity lighting without a spike in energy use. In terms of spectral composition, daylight provides a full-spectrum

light with its energy peaking slightly in the blue-green area of the visible spectrum. This makes daylight the most efficient source of illumination, as the human visual system is most sensitive to the blue-green portion of the light spectrum (Franta and Anstead, 1994; as cited in Edwards & Torcellini, 2002). The commonly used electric light sources including energy-efficient fluorescent lamps lack the blue portion of the light spectrum (Liberman, 1991; as cited in Edwards & Torcellini, 2002). The full-spectrum lighting is also known to be important for human biological needs (Pauley, 2004).

Besides the physiological benefits, daylighting has been associated with many psychological advantages. Data from several field studies has linked daylighting to improved productivity in schools and offices, higher sales in retail stores, shorter recovery time in hospitals, improved mood and wellbeing, lower occurrence of headaches, SAD, and eyestrain, and increased job satisfaction, work involvement, and organizational attachment in workspaces (Veitch & Gifford, 1996b; Heschong, 2002; Heschong, 2003; Edwards & Torcellini, 2002). It has also been reported that companies have seen a reduction in office worker absenteeism after moving to new office buildings that integrated daylight (Romm and Browning, 1994; Sundaram and Croxton, 1998; as cited in Edwards, 2002).

Another important psychological aspect of daylighting is meeting a need for contact with the outside environment (Robbins, 1986). Daylight brings a natural element into the built environment and keeps us aware of the changes in nature through its constant alteration in color and intensity. Also, the view of outside through windows has been linked to similar psychological benefits as daylight. Heschong Mahone Group investigated the influences of indoor physical environment on office worker performance

and found that an ample and pleasant view was consistently associated with better office worker performance, while glare from windows had a negative effect on that (Heschong, 2003). Newsahm et al. (2009) studied an open-plan office building in Michigan and indicated that window access at the desk is a significant predictor of satisfaction with lighting, particularly through its effect on satisfaction with outside view.

1.2. PROBLEM STATEMENT

In recent years, the use of automatic controls has become an inevitable part of an energy efficient building. Green building rating systems do not acknowledge occupant-controlled lighting and shading as an energy-saving strategy. This has arisen from observational studies that show occupants do not use their manual controls frequently and effectively (Rubin, Collins, & Tibbott, 1978; Rea, 1984; Linsay & Littlefair, 1993; Foster & Oreszczyn, 2001; Moore et al., 2003b; Boyce et al., 2006b; Konis, 2012). Consequently, the use of daylight-linked automatic lighting controls has become part of building code requirement. ANSI/ASHRAE/IES 90.1-2010 (Commercial Building Energy Standard Section) requires the use of daylight-linked lighting controls in buildings with more than 250 ft^2 of daylit area.

Although automatic lighting controls reveal substantial energy savings in laboratory and energy modeling tools, evidence has accumulated that they do not perform to their full capacity in real buildings (Heschong, Howlett, & McHugh, 2005; Williams et al., 2011). Typically user behavior is found to be responsible for the systems' poor performance (Foster & Oreszczyn, 2001; Reinhart 2004). For example, the performance of photoelectric lighting control is usually affected by occupants' use of blinds to control glare in daylit spaces. A small time interval of direct sun in early morning or late

afternoon can lead to blinds being employed by an occupant and then left in place for days, which in turn prevents the photoelectric lighting controls from dimming the lights during the daylight hours.

To address this problem, automated shading systems have been developed to be integrated with lighting controls. Once again, while the automatically controlled blinds theoretically have the potential to reduce energy consumption and peak demand (Lee, DiBartolomeo, & Selkowitz, 1998; Vartiainen, Peippo, & Lund, 1999; Athienitis & Tzempelikos, 2002; Roche, 2002; Inkarojrit, 2005), their application in many buildings have not been successful due to technical and operational problems (Mahone, 1989; Bordass, Bromley, & Leaman, 1993; Jain, 1998; Bordass et al., 2001; Stevens, 2001). Observations and occupant interviews reveal that occupants are often dissatisfied with the automated blinds and try to override or disable them (Bordass, 1993; Stevens, 2001; Inkarojrit, 2005). Considering the substantial expenses of automatic controls, it is not reasonable to install these systems to be constantly overridden.

On the other hand, it has long been acknowledged that people must be given control over their work environment, not only because preferred environmental conditions will be provided for individuals, but the state of perceived control itself is appealing (Veitch, 2000). In fact, studies of health and productivity in office buildings show that increasing the perceived level of individual control improves users' well-being and productivity (Barnes, 1981; Wilson & Hedge 1987; Bordass, 1993; Veitch, 2000; Newsham et al., 2004). However, occupants must be given control in the right context where they can use their controls adequately and be integrated into the cycle of energy efficient buildings.

Accordingly, before jumping into conclusion that occupant-controlled environments are inherently not green, we need to reconsider our design solutions. The purpose of this dissertation is to introduce conditions in which occupants use their allocated shading and lighting control in an energy efficient manner. Such condition has many benefits including higher user satisfaction and awareness, as well as the elimination of the unnecessary costs of over-automatization of the buildings.

1.3. RESEARCH OBJECTIVES

Since occupants are key determinants of building energy performance, the main objective of this research is to find a solution to actively involve occupants in the daylighting of the buildings. Studies that demonstrate occupants' infrequent use of lighting and shading controls have mostly been done in spaces with poor daylighting design. In these buildings, occupants often control shading devices on windows with no glare control and in conditions where they do not feel comfortable using their controls. This has resulted in the abrupt assumption that occupants are incapable of using their controls effectively.

Consequently, simple daylighting strategies are giving their place to complex automatic systems. Daylighting strategies such as subdividing the window height into two sections of "daylight" and "view" or the use of horizontal shading devices to control glare on windows. This dissertation aims at investigating the effect of a subdivided window with horizontal shading devices on occupant use of blinds and electric lighting. Subsequently, the dissertation examines a number of design options for a subdivided window featuring a combination of manual and automatic shading devices for optimum daylight performance and occupant satisfaction.

1.4. RESEARCH QUESTIONS

The main questions in this research are as follows:

1- Does a subdivided window in which occupants control the blinds on the lower half of the window affect their shade and light control behavior in an open plan work environment?

2- What type of treatment should be installed on the upper part of the subdivided windows to enhance their daylight performance?

3- What type of evaluation method should be used to investigate the daylight performance of the subdivided windows?

1.5. APPROACH

The general structure of this dissertation can be described as a design-decision research in which a research-based knowledge is applied to a design problem (Farbstein & Kantrowitz, 1991). The research was performed using two strategies: a quasi-experimentation and simulation. The quasi-experimentation mainly addressed the first research question and provided a foundation for the second part of the research. An open plan studio space at the School of Architecture and Urban Planning, University of Wisconsin-Milwaukee was selected as the case study. This setting was selected because it had the potential to be a well-daylit space, while the window shading design did not accord with prevailing daylighting guidelines.

For this study, the room was divided into two sections along the south-north axis: The subdivided window zone and the original window zone. The windows in the subdivided window zone received new shading devices as an intervention. The occupants in the original window zone served as the control group. Occupants' use of venetian

blinds and electric lighting as well as occupants' attitude toward the shading design was recorded and compared in the two zones. Since students were not assigned randomly to each condition, this study could not be defined as an experiment. However, the two groups were substantially equal in terms of age, education, income, and cultural background. Therefore, the first phase of the study was designed as a quasi-experiment (Campbell, Stanley, & Gage, 1963).

The second research question was investigated using a highly validated daylight simulation program called Radiance. Radiance simulation tool helped calculate illuminance levels and glare sensation probability for window alternatives and estimate the lighting energy saving potential of each subdivided window design. This question was examined in two chapters. First, four subdivided window alternatives with interior shading devices were simulated in five different climates. The next chapter compared the performance of an internal shading device with that of an external shading device installed on the upper part of the subdivided windows.

Before investigating the subdivided window alternatives, it was necessary to establish which daylight performance metrics should be used to differentiate the design options. This was especially important in terms of glare metrics, as there is not still an agreed upon visual comfort assessment method among the daylighting experts. The validity of the glare evaluation methods was investigated using field measurements in Mount Angel Abbey Library. HDR images were captured inside the Alvar Aalto's distinguished library, and visual comfort was assessed using a number of currently used methods. The accuracy of the methods in prediction of glare sensation was evaluated based on the author's visual experience in the space.

1.6. SCOPE AND LIMITATIONS

The flied study and the simulations performed in this research have a number of limitations. The flied study was conducted on 40 participants with similar age and cultural and educational background. The study needs to be repeated in different locations with more diverse study populations to ensure its external validity. In terms of internal validity however, the research relies on occupant's actual behavior, and the author's subjective judgment does not derive the conclusions. Occupants' shade control behavior was observed using photography. The lighting energy use and illuminance levels were also recorded by instruments, reducing the chance of bias and researcher's interference in this study. The research methods are described precisely and experiments are replicable.

Regarding the simulation studies, the validity of the Radiance simulation was tested by comparing the luminance values achieved through an HDR image and Radiance rendering of the studied space. The result demonstrated a close match between the two images. The main limitation in the simulation study was time. The 5-phase method for simulating complex fenestration with Radiance is time-consuming. With cloud computing the processing time was reduced, but it would be quite costly to render several views of the interior space.

1.7. ORGANIZATION OF THE DISSERTATION

Chapter 2: Reviews previous studies on the occupants' control over their environment and the performance of occupant-controlled and automatically controlled shading and lighting devices. It also discusses the challenges of designing an optimum daylight control system.

Chapter 3: Describes the field study of occupant shade and lighting control behavior in two conditions: 1- occupants controlling the shades on a subdivided window, and 2- occupants controlling the shades on a conventional window.

Chapter 4: Introduces the current daylight performance metrics and validates the glare evaluation method used in this dissertation.

Chapter 5: Investigates the daylight performance and lighting energy saving potential of four subdivided window alternatives using Radiance simulation.

Chapter 6: Compares the daylight and energy performance of two subdivided windows with external and internal shading devices with that of the existing windows in an open plan studio space. This study was also conducted using Radiance simulation program.

Chapter 7: Summarizes the study and recommends directions for future research.

CHAPTER 2
Literature Review

This chapter reviews previous research on occupant control over environmental conditions in general and daylight and electric lights in particular. It also discusses the challenges of designing an occupant favorable daylight control system.

2.1. OCCUPANTS' CONTROL OVER ENVIRONMENTAL CONDITIONS

It has become evident that the physical environment in which people work affects both performance and job satisfaction (Brill, Margulis, & Konar, 1985; Clements-Croome, 2000; Davis, 1984; Dolden & Ward, 1986; Newsham, Veitch, Charles, Clinton, Marquardt, Bradley, Shaw, & Readon, 2004; Vischer, 1989, 1996; as cited in Vischer, 2007). Veitch et al. (2007) collected 779 open-plan office occupants' opinion regarding their satisfaction with privacy, acoustics, lighting, ventilation, and temperature in their work environment. The questionnaire data analysis revealed that occupants who rated their work environment more positively were also more satisfied with their job.

In another study, physical and questionnaire data collected from 95 workstations at an open-plan office building in Michigan demonstrated a significant link between overall environmental satisfaction and job satisfaction, mediated by satisfaction with management and with compensation (Newsahm et al., 2009).

One of the important aspects of the physical environment is the availability of choices and the degree of occupants control over their environment. Occupants' control over their environment is discussed in three different levels. The first level is the idea of perceived freedom. As Barnes (1981; as cited in Veitch & Gifford, 1996a) describes it "perceived freedom is the recognition that one has alternatives in the physical

environment from which to choose”. The next level is perceived control. A perceived control is the perception that one’s choices determine outcomes (Barnes, 1981).

Accordingly, perceived control exists when one can predict the outcome of a particular choice, while perceived freedom is related to the availability of options and accompanies the possibility of failure when a wrong choice is made. The third level is exercised control, in which the occupants use their controls to achieve their desirable condition. Environmental psychologists have studied these three levels and have found varying outcomes in terms of their impact on occupant well being and performance.

2.1.1. Perceived Freedom

Some psychologists, including Barnes (1981), believe that the availability of choices in the physical environment alone is beneficial as it prevents the detrimental impacts of the lack of control. Barnes believes that “experience with perceived freedom will lead to perceived control, and increase in perceived control (the belief that one can predict the consequences of environmental choices and can cause desired changes to conditions) will increase satisfaction with the built environment.”

It is held by many other researchers that availability of choices is necessary to individual's well-being and it will lead to desirable outcomes such as increased productivity (Averill, 1973; Burger, 1989; Gifford, 1987 as cited in Veitch and Newsham 2000a), while the absence of control leads to feelings of unhappiness and helplessness and incites stress reactions (Averill, 1973; Burger, 1989; Seligman, 1974; as cited in Veitch 2001).

Some environmental psychologists however do not fully embrace this idea. They notify us that control can become a stressor in situations where one fears looking unwise

by making the wrong choice. Burger (1989; as cited in Veitch & Gifford, 1996a) observed that people declined control when it carried the risk of failure, or if it created uncomfortable concern with self-presentation. Wineman (1982; as cited in Veitch & Gifford, 1996a) similarly argues that "control can lead to undesired effects if it requires choices one did not wish to make." Furthermore, experts maintain that providing too much control can be overwhelming (Becker (1991; Barnes, 1981; as cited in Veitch and Newsham 2000a). In a high-demand job, additional choices concerning the physical environment could contribute to overload (Wineman, 1982; as cited in Veitch and Gifford, 1996a).

In defense of this argument, Veitch and Gifford (1996a) provided participants with control over the lighting, in the form of choices between three pre-set lighting configurations (1- ambient light only, 2- ambient and incandescent task lighting, 3- ambient plus compact fluorescent task light) in a windowless experimental setting. They maintained 750 lux mean horizontal illuminance in all three configurations. At the beginning of the experiment, all of the participants rated the three workstations from least preferred to most preferred. Then the choice group did the performance tests under their most preferred lighting configuration, but the no-choice group did the tests under the lighting condition assigned by the experimenter.

The result showed that although the availability of choice led to perceived control, it did not have a positive effect in participants' performance on the creativity task. Veitch and Gifford concluded that providing choices is not, per se, beneficial for people. They however, point out that the experimental condition could be responsible for participants' poor performance, as no feedback was provided for the subjects about whether they made

a correct decision on lighting. Therefore, providing choice (perceived freedom) does not always lead to better mood or performance. It is very important that choice be provided with feedback and information.

2.1.2. Perceived Control

Unlike the perceived freedom, most psychologists agree on the benefits of the perceived control. Researchers have studied the relationship between user performance and the perceived control over visual, acoustic, and thermal conditions of their environment. Glass and Singer (1972, as cited in Veitch & Newsham 2000a) studied the effect of control over noise on cognitive task performance. They realized when the noise was predictable, or when the participants were informed that they can stop the noise by flipping a switch, they showed better proofreading performance and better post-exposure frustration tolerance, even though the noise exposure was the same as in unpredictable noise session.

Sherrod (1974; as cited in Veitch & Newsham 2000a) did a similar study, but he used crowding as a stressor. He reported positive effects regarding perceived control when the participants were provided with the option to leave the crowded setting as the controller. Veitch (1990) investigated the effect of control over office noise and illumination on reading comprehension. She noted that subjects performed better in their tasks when the noise source was internal; that is, it was caused by their own activities. And they performed poorly when the noise was caused by an external source; that is, the noise source was not under their control.

Wyon (2000) found that office designs that allow the occupants to adjust the background levels of white noise are much more desired than open landscape offices.

Kroner et al. (1992) showed that the rate at which insurance claims were processed in an insurance company increased by 2.8% when individual control over temperature was operative (Wyon, 2000).

Lee and Brand (2005) asked participants from five different organizations to rate their physical environment aspects such as their control over the organization/appearance of their work area, their ability to personalize their workspace, their ability to re-arrange the furniture, and the availability of the variety of work environments. The comparison of this data with occupants' rating of their job indicated that perceived control had a significant, positive influence on both job satisfaction and group cohesiveness due to flexible use of space. Additionally, they found a link between job satisfaction and perceived (self-reported) performance.

Similar trends have been observed in lighting control. Many lighting researchers believe that people with personal controls will be more satisfied and productive in their workplace (Barnes, 1981; Simpson, 1990; Newsham et al., 2004), not only because preferred luminous conditions will be provided for each individual, but the state of perceived control itself is appealing (Veitch, 2000).

2.1.3. Exercised Control

Veitch and Newsham (2000a) conducted an experiment to study the effect of exercised control on occupants' mood, satisfaction and performance. They provided the first group of participants with dimmers to adjust the lighting to their preferred condition. The second group of participants had to complete the required tasks under the lighting conditions that a previous participant had arranged without the ability to change it. The results showed that although participants in the choose session reported greater perceived

control over lighting than their succeeding partners, the two groups were similar in clerical and creative writing task performance, mood, and satisfaction. The authors indicated that the results could be affected by the fact that the environmental condition was too good. They concluded that when the environmental conditions are within an acceptable range and no serious source of stress exists, the presence of control is unimportant.

Paciuk (1989 as cited in Veitch & Gifford, 1996a) investigated occupants' attitude toward control over thermal environment. She found that availability of thermal control (e.g. adjustable thermostats, window blinds) and the perception of control both contributed to thermal satisfaction. However, the exercise of control decreased thermal satisfaction.

2.1.4. Summary and Conclusion

Psychologists unanimously indicate that user control over their environment is one of the key factors in producing healthy workplaces (Bordass, Bromley & Leaman, 1993; Roulet, et al., 2006; Newsham et al., 2008). Based on the assumption that people do not use their controls effectively, Green Building Rating systems do not recognize user-controlled environments as an energy efficient approach. Recently, however, there is an increased awareness and emphasis among the design community on the role of building occupants in the energy performance of the buildings. This means that architectural design is deviating from looking at buildings as independent machines, and is paying more attention to integrating occupant into the environmental control loop.

This trend is evident in the 2009 PLEA (Passive and Low Energy Architecture) Conference manifesto (Cole, 2010). The conference was held with the ambition to

recognize building inhabitants as “key active determinant of energy performance in passive design”. The manifesto points out that “comfort is a relative state strongly dependent on the liberty to choose”, and that a dynamic interaction between the occupants and the buildings can lead to reduced energy consumption. Based on these assumptions, the design community is invited to “rehumanize” the architecture through providing adaptive opportunities for the occupants rather than automation (Cole, 2010).

Wyon (2000) notifies us that "bringing the user back into the loop is far more important for well-being and productivity than optimizing uniform conditions to accord with group average requirements." He also points out that users will complain less about their environment if they realize that there are solutions for their complaints, and this will reduce the unexpected cost of handling complaints. To make effective use of their controls, Wyon (2000) proposes that users need three essential elements: information, insight, and influence. "They must understand the way the building works and the consequences of their actions, so they must be given Insight. They must learn to use the control delegated to them, and as learning cannot take place without feedback, they must be given Information. Only when they have both Insight and Information can they be given Influence."

2.2. OCCUPANT CONTROL OF SHADING DEVICES

It has been a few decades since daylighting scholars have notified the design community that occupant use of blinds must be taken into account when calculating energy saving potential from daylighting. This issue has motivated a number of shade control behavior studies looking at factors that trigger occupants to adjust their shades.

2.2.1. The Effect of Window Orientation and Outdoor Conditions

The early studies of occupant use of blinds focused on outdoor environmental conditions and facade orientation as influential factors. For instance, Rubins, Collins, and Tibbott (1978) monitored the manual control of blinds in private offices facing north or south. They used a five-level rating scale to estimate blind height and a two-level (open and closed) rating scale to evaluate the angle of the blinds. The data analysis showed a higher window occlusion in south compared to north facades, and the authors concluded that people use the blinds to block direct sunlight. They also noticed that only in 7% of the observed windows the blinds were adjusted more than once per day.

Rea (1984) photographed the south, east and west facade of a 16-story office building in Ottawa, Canada, at three times of the day once on a cloudy and once on a clear day. Rea extended Rubin et al.'s 5-level occlusion scale to an 11-level occlusion scale, but ignored the slat angles in his calculations. He found that time of day was not a significant factor in occupants use of blinds, as occupants made little or no change to blind position throughout the day even in east and west facades on the clear day. The sky condition largely affected the blind use on the east facade, but not on the south and west facade. In terms of window orientation, there was a small but consistent difference in the occlusion value between the three facades. Rea maintained that people use window blinds to block direct sunlight, thermal radiation, or both, but they do not change the blinds actively in response to these stimuli; rather, their preference for window blind position is based on long-term perceptions of solar radiation.

Further studies supported the variability of the blind operation with the window orientation (Inoue, Kawase, Ibamoto, Takakusa, & Matsuo, 1988; Lindsay & Littlefair,

1992; Pigg, Eilers, & Reed, 1996; Foster & Oreszczyn, 2001; as cited in Inkarojrit, 2005). In these studies researchers started to pay more attention to solar radiation data as an exterior variable. Inoue et al. (1988) recorded the direct and diffuse solar radiation and for the first time, they were able to establish a correlation between the occlusion value and the amount of solar radiation incident on a façade. Lindsay and Littlefair (1992) also noticed a connection between the operation of blinds and the amount of sunshine present and the position of the sun. They hypothesized that people use blinds to avoid glare rather than to prevent overheating.

Foster and Oreszczyn (2001) videotaped blind movement in three offices in London, England. They calculated the occlusion index by multiplying blind position (0=fully open, 5= fully closed) and blind slat angle values (1=horizontal, 2=between horizontal and vertical, 3=vertical). The sunshine index was a function of weather code (1=overcast, 2=slightly cloudy, 3=sunny) by time code (1=early(1=early morning or late afternoon, 2=mid afternoon, 3=midday). They found that occupants don't operate blinds in response to solar availability. They also noted a weak relationship between the degree of sunshine and the occlusion index.

2.2.2. The Effect of Indoor Conditions

In the subsequent group of studies, researchers started to take into account the interior environmental conditions in addition to sky condition, facade orientation, and incident solar radiation. Raja, Nicol, McCartney, and Humphreys (2001; as cited in Inkarojrit 2005) found that blind occlusion increased with an increase in indoor and outdoor air temperature. The rate of change, however, was small. Raja et al. confirmed Lindsay and Littlefair's hypothesis that the reason for using blinds is to avoid glare rather

than to reduce heat. Nicol (2001; as cited in Inkarojrit 2005) also came to the conclusion that solar intensity would be a better predictor than outdoor temperature for explaining blind usage.

Reinhart (2001) monitored occupant shade control behavior in 10 daylit offices. Blind settings in the offices were recorded using a video camera and the blind occlusions were manually extracted from the collected digital images. Meanwhile, direct and diffuse irradiances and the facade illuminance were collected by a sensor on the roof. The blind occlusion corresponded to the percentage of a window that was covered by blinds, and it was independent of the blind slat. The correlation study between sunlight level and blind adjustment revealed that occupants lower the blinds when direct sunlight (ambient direct solar irradiance onto the façade) lie above 50 W/m^2 and incoming solar gain is above 50 klux (450 W/m^2). Based on these findings, he developed a shade control behavioral model which is implemented in a few energy simulation programs.

Inkarojrit (2005) conducted a two-phase study on occupants' control of venetian blinds in private offices. In the first phase of study, he collected survey data from 113 participants from 9 office buildings in Berkeley, California. The main findings of the survey are as follows: 1- Reducing glare from sunlight and bright windows is the primary reason for closing the shades; thermal comfort and visual privacy are secondary reasons. 2- The majority of building occupants (77%) rarely adjusted their window blind positions and slat angles on a daily basis; however, sky conditions had an influence on the frequency of window blind adjustments. 3- Window blinds were primarily opened to increase the level of light/daylight in workspace and to maintain visual contact to the outside for all façade orientations.

In the second phase, Inkarojrit studied blind usage pattern in relation to indoor environmental conditions such maximum window luminance, average window luminance, background luminance and vertical solar radiation transmitted through the window, mean Radiant Temperature, and direct solar penetration. He derived window blind control models which predicts the probability of blinds being lowered based on the intensity of the stimulus. For example, the model predicts that there is a 50% likelihood that a shade will be lowered when the transmitted vertical irradiance is 13 W/m2. At 100 W/m 2, the model predicts that 90% of shades on a given facade will be lowered. Inkarojrit's model, however, does not predict shade raising events.

Nicol, Wilson, and Chiancarella (2006) studied 26 European office buildings on a monthly basis. They monitored outdoor and indoor environmental conditions as well as occupant behavior in terms of blinds and electric lighting usage. They also collected occupants' subjective evaluations of their workplaces. The data showed that the use of lights was more linked to the external illuminance levels, while the use of blinds was more affected by the weather. Between the 26 buildings, there was a noticeable difference in the use of lights, while the blinds were consistently used to cope with the heat and glare on sunny days. Occupants generally seemed to use the blinds and electric lighting to balance illuminance condition, but the adjustment rarely happened during the day. Finally, the Illuminance level and the use of lights and blinds did not seem to affect occupants' self-reported productivity.

Mahdavi et al. (2008) studied occupant control of shades and electric lighting in three office buildings in Austria with various window orientations. They examined the relationship between the control actions and environmental conditions such as indoor and

outdoor temperature, internal illuminance, external air velocity and global irradiance. They maintained that their observations did not reveal a clear relationship between the opening shade actions and the incident radiation on the facade, while the closing shade actions were somewhat more predictable. They noticed that the frequency of the closing shade actions increased once the incident radiation rose above 200 W/m2 in one of the studied buildings. This threshold is much higher than what was previously found in shade operation studies.

2.2.3. The Effect of The Location and Type of Control

Escuyer and Fontoynont, (2001) studied 41 French office workers attitude toward lighting control system and use of blinds in three different buildings. In one of the buildings, occupants complained about blind controls not being easy to access and manipulate, which resulted in infrequent opening of the blinds and relying on electric lighting. Occupants generally deemed daylight presence to be important and preferred the blinds to be open, however problems such as reflections on the computer screen, which could be avoided by repositioning the screens, stopped them from opening the blinds. Similar to other studies, the authors noticed that once lowered occupants forget to raise the blinds after daylight glare is eliminated.

Sutter, Dumortier, and Fontoynont (2006; as cited in Reinhart 2006) monitored occupant use of remotely controlled black Venetian blinds and standard manually controlled fabric blinds in 15 offices over 30 weeks. They noticed that access to a remote control increased the chance of blinds being manipulated by the occupants. The authors also found that brighter VDU screens lead to office workers tolerating higher daylighting

levels on the screen, thus allowing more daylight in a space for ambient lighting (Reinhart 2006).

Mahdavi et al. (2008) noticed that occupants demonstrated different shade deployment behaviors based on the control type. They observed that there was a more meaningful relationship between the shade deployment and the magnitude of solar radiation with mechanically supported shade operation system than with the fully manual shade operation system. Occupants who controlled external motorized screen shades by using a switch under the window showed a different level of shade deployment in the summer compared to the winter months, whereas occupants who used fully manual shade operation system showed a relatively small variation in the monthly shade deployment. The authors assumed the easy manipulation of the shades in the latter system might have been influential in occupants' behavior.

2.2.4. Shade Control Behavioral Models

Occupant shade control studies have resulted in shade control behavioral models used in building energy simulations. The current models are based on two general hypotheses. The first hypothesis, known as "active operator" hypothesis, assumes that occupants lower the shading devices in response to the magnitude of transmitted vertical irradiance or the presence of direct sun on their workplane and retract the shades either in the next morning or when the stimulus is within acceptable range (Lee and Selkowitz, 1995; Reinhart, 2002; HMG, 2010; as cited in Konis 2012).

The second hypothesis, known as " passive operator" or "worst case scenario" hypothesis, is based on observations that occupants position shading devices according to their long term perception of "worst case" solar condition, and do not adjust the shades

on a daily basis (Rubin, 1978; Rea, 1984; Foster and Oreszczyn 2001; Inkarojrit, 2005). Table 2.1 shows some of the discussed shade control behavior models.

Table 2.1: Some of the Existing Shade Control behavioral Models (Konis, 2011)

Model	Criteria for lowering	Criteria for raising
Reinhart, 2002	If irrad > 50 W/m^2	Shades raised on arrival on following workday
Lee and Selkowitz, 1995	If irrad > 95 W/m^2	If irrad < 95 W/m^2, shades raised after one hour
LEED, 2012	If direct sun incident on workspace	If no direct sun incident on workspace, shade raised
Inkarojrit, 2005	If irrad = 13 W/m^2 50% probability	NA, shades are not raised

Konis (2012) examined the existing hypotheses on occupant shade control behavior through time-lapse observations. He monitored occupant shade control behavior in relation to several environmental factors in the San Francisco Federal Building. This study was different from the previous field studies, as it looked at windows which were subdivided into a lower vision zone and an upper daylight zone, and it was done in open-plan offices. Occupants manually controlled interior roller shades installed adjacent to the lower and upper windows of the facade. Konis used an innovative survey collection system in which occupants were prompted with questions simultaneously as the survey device was measuring the indoor temperature and illuminance level, and cameras were taking HDR images.

His observations showed that the “active operator” shade control models underestimate the window occlusion, and the “worse case” model overestimates the level of window occlusion, but it predicted it more closely. In other words, occupants did not adjust interior shading devices on a daily basis in response to the magnitude of transmitted vertical irradiance or the presence of direct sun on workspaces. This result

supports the hypothesis that shade positions are based on perceptions formed over long periods of time and is not affected by seasonal variation in solar conditions.

Konis also notifies us of another error, in that the existing behavioral models that assume occupants either fully retract or fully deploy shades, while occupants in this study often left the lowest 20 to 40% of vision windows unshaded to keep a visual contact with outside. He also found that the upper two rows of windows, designed for daylight transmission to the core, were predominantly shaded on both north-west and south-east facades, and occupants adjusted the lower shades more often that the upper shades. The HDR image analysis indicate that maximum and average window luminance is a better predictor for occupants use of shades than the transmitted vertical irradiance. The survey results suggest that, for the majority of participants, shade control behavior was not influenced by concern for the comfort of coworkers.

2.3. OCCUPANT CONTROL OF ELECTRIC LIGHTING

Several Field and laboratory studies have indicated that office workers prefer having control over lighting, and they associate this control with their satisfaction and productivity. Occupant control of lights however, is generally deemed to reduce building energy efficiency based on behavioral observations. Independent studies show that giving control over lighting produces a common pattern of behavior. The occupants use the switching or dimming controls to adjust the light level at the beginning of the day and rarely change it throughout the day (Boyce et al., 2006b; Moore et al., 2003b).

2.3.1. The Effect of Daylight Level

There has been some evidence that daylight availability affects occupant use of electric lighting controls. Based on field and experimental observations, people are less

likely to switch on electric lighting upon arrival as daylight level increases inside the room (Hunt, 1979; Love, 1998; Reinhart & Voss, 2003; Lindelof & Morel, 2006; as cited in Reinhart 2006). Mahdavi et. al (2008) studied occupant use of shades and electric lighting in relation to environmental factors and found that the light switch-on probability increases significantly only when the horizontal illuminance level at the proximity of workstation is below 200 lux.

This is a common pattern of behavior for those who consider daylight when switching the lights. It has also been observed that people turn the lights on automatically upon arrival with no consideration of daylight levels (Boyce et al., 2006b). In both cases though, once the lighting is on, users do not tend to switch it off until they leave the office (Hunt, 1979; Boyce, 1980; Love, 1998; Boyce et al., 2006b).

In terms of the effect of daylight on occupants' preference for electric light level, studies have revealed controversial results. Escuyer and Fontoynont (2001) observed that people tended to choose a lower level of electric light when more daylight entered the office. Others found that occupants' choice of illuminance level were independent of or weakly related to daylight, when they were provided with individual dimming controls (Moore et al., 2003b; Yoshida-Hunter, 2003; Boyce et al., 2006b). In one study, users even increased the amount of electric lighting in a deep private office as the illuminance from daylight increased, possibly to brighten the back of the office and reduce the contrast (Begemann et al., 1997).

2.3.2. The Effect of the Location and Type of Lighting Control

The location of the manual lighting control is another influential factor in their usage pattern. Maniccia et al. (1999) showed that office workers adjust the lights more

often if the dimming control is located at their desks. This produced 6% savings in energy consumption (Maniccia, Rutledge, & Rea, 1999). Moore et al. (2002a; 2002b) studied user attitude toward locally controllable dimmable lighting systems in open-plan office spaces. 410 people located in 14 buildings participated in this research. Occupants showed more positive attitude toward the user controlled lighting system compared to the lighting installation without user control, while latter created lighting condition that matched more closely to the recommended illuminance levels and luminance ratios.

A significant number of workers chose illuminance levels below the recommended values (below 300 lux in daylit offices and below 750 lux in deep plan offices). Users typically set the controls at 50% of maximum lamp output, without a decrement in their perceived lighting quality. This is possibly because users had a chance to easily estimate the desired amount of light when exercising control at the workstation (Moore et al., 2002a). They also found that users selected a wide range of luminaire outputs influenced by their age and the proportion of the day spent using a monitor (Moore et al., 2002a). People with dimming control also showed more sustained motivation over the workday.

These studies, along with many others that confirm the diversity of office workers' preferences in illuminance level (Escuyer & Fontoynont, 2001; Boyce et al., 2006b), has led to the recommendation of individual dimming control of lights in shared offices. The benefits associated with the provision of such control are as follows: improved work performance, environmental satisfaction, and energy savings (Boyce et al., 2006b).

The first two benefits are linked to occupants' ability to obtain their desired illuminance, and the energy savings from individual control is justified by the possibility of switching lights off when not in use as well as users' choice of illuminance levels (Boyce et al., 2006b). The fear of conflict in shared spaces usually inhibits the users from switching or dimming the general lighting, whereas with individual control over local lights, occupants will be more likely to switch the lights off when they leave their workstation (Newsham et al., 2008).

In addition, personal dimming control bears energy saving potential due to the fact that occupants usually adjust the lamp outputs to illuminance levels below the recommended values (Moore et al., 2002a; Moore et al., 2003b). Studies in laboratories with little or no daylight illustrated that personal dimming control creates more energy savings than a fixed lighting designed to prevailing recommended practice (Newsham et al., 2008). Some, but not all, laboratory and field studies showed that with the presence of daylight, this energy saving was increased (Newsham et al., 2008).

The main concern with individual control is, however, the frequency of use. It is expected that individual dimming or switching control not be used regularly unless there is a noticeable variation in the visual difficulty of the tasks done (Boyce et al., 2006b). Therefore, with appropriate means, occupants must be reminded of adjusting their lights when daylight reaches the adequate level.

There is also a discussion about using bi-level switches (full, 2/3, 1/3) versus dimmers (Jennings et al., 2000). One research showed that people intend to use bi-level switching more effectively than manual dimmers (Maniccia, et al., 1999). The data illustrated that almost all apparent dimming was either between 90 and 100% of full

power, or between 0 and 10% of full power. In other words, users slid their dimmers either all the way up or all the way down. This could be due to the fact that it is easier to choose from few switch positions than to adjust a dimmer to a particular position. Although, it needs to be determined whether providing instructions in the use of dimmers would affect their use (Jennings et al., 2000).

Different strategies are proposed to provide individually controlled local lighting for workstations. Task-ambient lighting design is one approach recommended in office lighting guidelines (IESNA 2000, p 26 –1; ANSI/IESNA 2004, p 21). The design guides commonly propose to reduce ambient lighting levels and add local task lighting of much lower wattage (Newsham, Arsenault, Veitch, Tosco, & Duval, 2004). This strategy is also featured in green building rating systems (Newsham et al., 2004). A group from Lawrence Berkeley National Laboratory installed desk lights with a luminous shade in a 14-person open-plan office. They observed that ambient lighting that was less used after the addition of desk lights, resulting in 50% energy savings, and the new lighting system was evaluated positively by the occupants (LBNL, 2004; Newsham et al., 2005).

Tiller et al. (1995) studied a field site that replaced all centrally-controlled ambient luminaires with locally-switched furniture-mounted indirect luminaires plus task lights. They reported energy savings of nearly 75%. Some studies show the opposite results in terms of energy use (Collins et al.,1989; Newsham et al., 2004) or occupant satisfaction (Boyce e al., 2003; Newsham et al., 2004). Tabuchi et al. (1995) found that task lighting supplements rather than supplants ambient lighting, resulting in no energy savings. Newsahm et. al (2004) found that the provision of a task light did not change the chosen level of ambient lighting from ceiling-recessed parabolics. They also found that

the addition of task lighting had no significant effect on mood, satisfaction, or discomfort and improved task performance slightly (Newsham et al., 2004).

In task-ambient lighting, the type of luminaire (direct, indirect, direct/indirect) and the luminance ratios of task and ambient lighting are important issues to be considered. The IESNA (2000) recommends that "the luminance ratio between a task and adjacent surrounds should not exceed 3:1, and across a person's field of view, the ratio of maximum to minimum should not exceed 10:1." After studying a mock-up office, Bean and Hopkins (1980) concluded that task and ambient lighting should be at the same level. The studies of Veitch and Newsham (2000b) and Rea (1983) confirmed this result.

In terms of luminaire type, Boyce et al. (2003). observed that lighting designs with fully direct luminaires, were rated as comfortable by 70% of participants, direct/indirect systems by ~80%, and direct/indirect systems with individual control by ~90% of participant. McKennan & Parry (1984) examined 10 different task-ambient lighting designs with an ambient lighting level of only 200 –250 lx. Participants favored luminaires suspended from the ceiling over local desk-mounted luminaires (McKennan & Parry, 1984). This could be explained by the fact that the suspended luminaires provided higher level of illuminance outside the immediate task area (up to 600 lx) and hence reduced illuminance ratios between task and the surrounding (McKennan & Parry, 1984; Newsham et al., 2004).

Veitch et al. (2008) conducted two experiments in a simulated office space and confirmed previous findings that direct–indirect lighting and personal control are favored over other lighting configurations.

2.3.3. Contemporary Workspace Requirements

As the use of computers and electronic devices is increasing the lighting requirements needs to be changed. A new concern is that direct illumination of the task is not required for self-luminous computer screen. Hence, in contemporary offices, occupants prefer to maintain illumination on vertical surfaces in order to create moderate luminance ratios in the field of view (Newsham et al., 2004). Escuyer and Fontoynont (2001) in a qualitative study of the acceptability of lighting control systems realized that people who work with computers tend to choose lower levels of illuminance (100–300 lux) on their workspace (Escuyer and Fontoynont, 2001). Also, with mobile devices and cloud computing, the future work environments can accommodate a flexible use of space where occupants easily change their location based on the type of the activity they perform.

2.3.4. Summary and Conclusion

Based on above discussions, occupant control of lights is not only essential for their well-being, but also offers energy saving potential. However, it is important that the manual lighting control be provided in the right context, and with adequate instructions. Manual switching does not fit the spaces where occupants do not feel responsible for light switching (Littlefair & Motin, 2001). We should also remember that the availability of the control is not per se beneficial. Newsham and Veitch (2004) notify us that the availability of lighting control is important to occupants who exercise their control to create their preferred conditions, and Veitch and Gifford, (1996b) indicate that "people with greater knowledge about lighting would prefer to control their lighting." So it is essential that control be provided with information.

2.4. AUTOMATIC SHADING CONTROLS

As discussed earlier, observations show that occupants do not use shading controls frequently and effectively. To address this problem, automated shading systems have been developed to increase the admission of daylight into the buildings. Given that the performance of automatic lighting controls is very dependent on the shading control, some experts have proposed integrated shading and lighting control systems.

2.4.1. Energy Saving Potential of Automatic Shading Controls

There has been a number of filed and simulation studies on the energy performance of the automatic shading controls. In a laboratory study, Clear, Inkarojrit, and Lee (2006) monitored the performance of an automatic shading system which was designed to maximize daylight energy savings while minimizing glare. The test rooms were equipped with automatically controlled switchable electrochromic windows (visible transmittance range from 3 to 60%) and venetian blinds, and 43 subjects worked for several hours inside the rooms. The author's recorded interior physical conditions along with the subjects' evaluation of thermal and visual comfort.

The results indicated that "net energy savings potentials are intimately linked to tradeoffs around providing glare control and daylight admittance." The shade control strategies that optimize glare will often switch the smart glass to its lowest light transmittance, increasing electric lighting use. The authors concluded that splitting the façade into an upper daylight window and a lower vision window will provide comfort and higher lighting energy savings.

Using a coupled lighting and thermal simulation module, Tzempelikos and Athienitis (2007) found that the integrated control of motorized shading and electric

lighting can substantially reduce the demand for cooling and lighting in the perimeter spaces.

US Department of Energy, Center for the Built Environment (CBE), and LBNL did a post occupancy evaluation of the New York Times building equipped with automatic lighting control, automatic roller shades and underfloor air distribution system (Lee et al., 2013). The reduction in annual electricity use due to the combination of all three systems was estimated to be 24% (2.58 kWh/ft2-yr) across a typical tower floor compared to a code-compliant building. Annual lighting energy use saving from automatic lighting control systems (occupancy, setpoint tuning, daylighting) was 56% compared to a code building. Annual heating energy use was reduced 51%. Peak electric demand was reduced by 25%.

Energy saving from automatic roller shades was not estimated separately. The data revealed that 80% of these motors were overridden an average of 18 times per year (1.5% of the year) for an average total time of 38 hours per year during primary work hours. 41% of the occupants responded with greater than neutral satisfaction with the automatic window shades, with an average rating on all 20 floors of 4.12 on a 7-point scale.

2.4.2. Occupant Attitude Toward Automatic Shading Controls

While the automatically controlled blinds theoretically have the potential to reduce energy consumption and peak demand (Lee, DiBartolomeo, & Selkowitz, 1998; Vartiainen, Peippo, & Lund, 1999; Athienitis & Tzempelikos, 2002; Roche, 2002; Inkarojrit, 2005), their application have not always been successful due to technical and operational problems (Mahone, 1989; Bordass, Bromley, & Leaman, 1993; Jain, 1998;

Bordass et al., 2001; Stevens, 2001). Observations and occupant interviews reveal that occupants are often dissatisfied with the automated blinds and try to override or disable them (Bordass, 1993; Stevens, 2001; Inkarojrit, 2005).

Vine et al. (1998) performed a pilot study on occupant response to an automated venetian blind and electric system. The system allowed for occupant override and showed a high level of acceptance by users, although some improvements were required like blind motor that produce a smooth and quiet blind motion. The study was short-term with a small number of participants (n=14).

Guillemin and Morel (2001) tested a self-adaptive integrated shading, lighting, and heating control system in an occupied office building during a four-month experiment. In this study, the automatic shading control system adjusted the blinds based on visual comfort when the user was present. When the user was absent, priority was given to reducing heating or cooling energy. The electric lighting controller adjusted the illuminance in the room up to the level desired by the user, which was learned by the system through the user's overriding actions.

Compared to their base-case control system which dealt separately with heating, ventilation, and lighting, the integrated system saved 25% more energy. However, user's were not satisfied with the automated shading system because it was not adaptive to their wishes like the lighting system was. When overridden, the system would be deactivated for about an hour, but then would return the blinds to the programmed level. Guillemin and Morel concluded that the control system should be designed to adapt itself on a long-term basis to the user wishes.

Reinhart and Voss (2003) studied 10 daylit offices in a two-story commercial building in Germany. The offices featured closed-loop automatic dimming controlled electric lighting and automatically controlled external venetian blinds with manual override, maintaining 400 lux on the work plane. Any manual blind manipulation disabled the automated blind control for 2 hours. The external blinds were supported by a lightshelf and consisted of an upper and a lower component. When the blinds were automatically lowered, the lower set of slats was closed, whereas the upper slats were kept horizontal to redirect daylight deeper into the room.

The blind occlusion data revealed that 45% of automated blind adjustments were corrected by the users. According to authors “this high correction rate confirms a previous finding that occupants consciously set their blinds – automatically controlled or not – and have a remarkably low tolerance range towards external readjustments.” Another finding is that in 88% of the times when the automated system lowered the blinds, the office workers manually retracted them; whereas, they rarely opposed an automated opening of the blinds. This strong tendency of the occupants to open the blinds was intensified at low solar penetration depths, endorsing hypothesis that “people accept their blinds to be extraneously opened than closed”. The only time occupants tended to close their blinds after an automated retraction was in winter afternoons when sun penetrated deeply into the building.

2.5. AUTOMATIC LIGHTING CONTROLS

Use of automatic lighting controls is becoming an integral part of green building design, while the actual performance of these systems shows that they often fail to provide the expected energy savings.

2.5.1 Energy Saving Potential of Automatic Lighting Controls

Current lighting design guides insist on the primacy of automatic lighting controls over user control of lights. IESNA lighting handbook suggests "local automated control techniques can be more cost effective than the usual reliance on manual operation of lights" (page 27-1 in IESNA, 2000). Automatic lighting controls fall into three major categories: 1- Occupancy / motion sensors, 2-Scheduled lighting controls, 3-Daylight-based controls (Photoelectric control) (Baker & Steemers, 2002). The most effective option depends on how much the space is occupied, and whether it is effectively daylit (Baker & Steemers, 2002). It is estimated that a properly designed automatic lighting control system reduces energy usage between 30% and 60% over a simple on-off system installation.

Rubinstein, Jennings, Avery, and Blane (1999) studied a daylight-linked lighting control technology at the Phillip Burton Federal Building in San Francisco. They determined that the annual energy savings for this type of daylight-linked controls was 41% and 30% for the outer rows of lights on the South and North sides of the building, respectively. The annual energy savings dropped to 22% and 16% for the second row of lights for the South and North, respectively, and was negligible for the third rows of lights.

Jennings, Rubinstein, DiBartolomeo, and Blanc (2000) studied control options in some private offices and found that the energy savings due to occupant sensing vs. dimming depended on the behavior of occupants: "In offices whose occupants tended to stay at their desks all day, dimming controls saved more energy, and vice versa." They also found that the integration of automatic dimmers and occupant sensors in private

offices could yield energy savings up to 43% compared to 23% and 26% savings of each system alone.

Li, Lam, and Wong (2006) studied the lighting energy use in an office space facing northwest (320 degrees) with automatic dimmable controls. They found that energy savings in electric lighting were over 30% using the high frequency dimming controls compared to electric lighting energy expenditure at night." This study does not provide any information about the shading type and occupants use of blinds to control direct sunlight.

Newsham, Mancini, and Marchand (2008) found that dimming lights can contribute large electricity demand reductions during periods of grid stress without major inconvenience to occupants. The level of dimming not noticed by occupants was 20 percent with no daylight, 40 percent with relatively low prevailing daylight, and 60 percent with high prevailing daylight (or, alternatively, an amount which represents 20 percent of total light level).

However, a number of field studies show that the performance of automatic controls have been overestimated as these systems are commonly disabled by users, often leading systems to default to high energy states (Love, 1995; Moore, Carter, & Slater, 2002a). A 2005 field study found that daylight-linked lighting control systems frequently fail in real buildings, and that functional systems save only around half as much energy as they theoretically could. (Heschong, Howlett, McHugh, & Pande, 2005).

Williams et al. (2011) did a comprehensive review of the literature on the energy impacts of lighting controls. They applied a series of filters to distinguish data points with significantly different characteristics and to remove possible sources of bias in the data.

Screening out data points that were not based on actual installations made a huge effect on the average estimated savings. Accordingly, they found that simulations appear to overestimate savings from daylighting. This result is not surprising, as daylight in a building is affected by multiple factors (building orientation, location, use, weather, occupancy, blinds, reflectances, commissioning, etc.) that may not be all accurately incorporated into a daylight simulation. However, the authors' comprehensive meta-analysis provides strong evidence that lighting controls can still reduce lighting energy use by one-quarter to one-third, depending on the individual control strategy, and up to nearly 40% for buildings in which multiple control strategies are used.

2.5.2. Shortcomings of Daylight-linked Lighting Control Systems

The performance of the photoelectric system is dependent on a number of factors including occupant behavior. Studies show that these systems function well at spaces that are inherently well-daylit with more uniform daylighting (Heschong, Howlett, McHugh, & Pande, 2005). However, there are several issues regarding the use of daylight-based automatic controls, also known as daylight harvesting systems.

One facet of the problem is the use of blinds to control glare in daylit spaces. With closed-loop photoelectric controls, in which the sensor is located inside the room, there will be no energy savings due to automatic control if the occupants keep the blinds closed all the time. In open-loop photoelectric system, in which the daylight sensor is located outside, the occupants will override the automatic control when the blinds are closed, because the room is not getting the expected amount of daylight.

Even an energy-conscious user that operates the blinds to maximize daylight admission can actually end up using more electric lighting than a user that keeps the

blinds lowered all the time (Reinhart, 2004). The reason for this apparent contradiction is that high internal daylight levels during departure prevent the former user from noticing that a dimmed lighting system is switched on. As a consequence, the lighting is regularly left on outside of regular working hours (Reinhart, 2004). To solve this problem, the new control systems include occupancy sensors. Multisensor systems featuring a photocell, and an occupancy sensor, however, only work well in private offices, as the false triggering of the occupancy sensor in open plan offices with reduces its energy saving potential (Granderson et al., 2010).

Another issue regarding the photoelectric lighting control is the occupants' range of preference in illuminance level. In automatic dimmers, the programmed minimum light level is usually set at a quite high point to accommodate all occupants' needs, while studies show that occupants have a wide range of preference in illuminance level (Galasiu & Veitch, 2006). Illuminance preferences are related to the ability to perform tasks as well as the workers' moods. Automatic controls provide uniform amount of light and cannot satisfy all the users (Boyce et al., 2006b). Some studies show that when given control, the occupants choose lower levels of light on their work stations compared to recommended levels (Moore et al., 2002a; Boyce et al., 2006a). This was the case in users that have monitors on their desks (Moore et al., 2002a). There have also been studies that show occupants choose higher levels of illuminance than the standard levels (Moore et al., 2002a).

The next shortcoming of automatic dimmable lighting arises from the control criteria in these systems. Commercially available lighting control systems work based on illuminance level measured by a sensor at the ceiling looking toward the work plane (Van

Den Wymelenberg & Inanici, 2009). However, a literature survey on determinants of lighting quality illustrates that unless at extremely low levels, illuminance is not an adequate indicator of satisfactory lighting condition for tasks (Van Den Wymelenberg & Inanici, 2009). Several studies have shown that, given a free choice, people in daylit spaces do not manipulate the lights to maintain constant desktop illuminance (Newsham, Aries, Mancini, & Faye, 2008). Their choices might be driven more by a desire to balance luminance or illuminance ratios (Halonen & Lehtovaara, 1995; Newsham et al., 2008) or by time-of-day effects (Begemann, 1997; Newsham et al., 2008).

Van Den Wymelenberg (2009) notifies that contemporary office occupants spend a significant amount of time working on computer monitors rather than horizontal tasks. Therefore, occupants' preferences in lighting can be better predicted by patterns of luminance in the vertical visual field than horizontal illumination (Van Den Wymelenberg & Inanici, 2009). Some researchers have proposed a luminance-based control system instead of illuminance-based lighting control. This system will use High Dynamic Range (HDR) imaging to evaluate the light distribution as well as illuminance levels at multiple locations and orientations (Sarkar & Mistrick, 2006).

Maintenance and calibration is also a major problem in the application of daylight-based automatic lighting control. In photosensor control systems, it is very crucial that the workplane illuminance and the photosensor signal be highly correlated. But in side-lit spaces this linear relationship does not always happen. The reason is that daylight distribution changes significantly with different sky and window blind conditions (Mistrick & Sarkar, 2005).

For instance, with the use of venetian blinds (e.g. angled at 30 degrees) the work plane receives relatively low illuminance, while the sensor's view of the window consists of the high-luminance sunlit ground. Such condition results in a high sensor signal to work plane illuminance ratio. The further photosensors are located from the window, the better they can predict work plane illuminance (Mistrick & Sarkar, 2005).

There can also be problems with using lighting controls with innovative daylighting systems like light-shelves, prismatic glazing and mirrors. Littlefair and Motin (2001) studied the effect of innovative daylighting system on the performance of automatic dimming controls. These devices redirect sunlight to the ceiling at certain times, affecting the ratio of the ceiling sensor illuminance to the workplane illuminance; while this ratio should be as constant as possible. The authors suggest the use of a partially shielded sensor - shielded from the window only, but open to the rest of the space - for spaces with innovative daylighting systems. However, an unshielded sensor receives light from the walls and correlate better with people's subjective judgment of the brightness of the space.

Another issue is sensor calibration. Sometimes closed loop controls are adjusted at night; while with innovative daylighting systems daylit calibration is also needed as the interior luminance distribution is very different with daylight compared to electric lighting (Littlefair & Motin, 2001). Littlefair and Motin (2001) finally conclude that with innovative daylighting systems the best alternative may be to abandon photoelectric control altogether, and use localized manual switching. The daylighting systems often uniformly illuminate a room without necessarily providing 500 lux on the workplane.

Under these circumstances people may well choose to leave the lights off; In addition people value individual, rapid response control.

Lastly, the automatic lighting controls are designed to maintain a fixed level of light on work plane. They do not let the occupants be aware of daylight changes. One of the main advantages of daylighting over electric lighting is that daylight is dynamic and creates vibrant and stimulating environments, while electric lighting is monotonous all day long.

2.5.3 Occupant Attitude Toward Automatic Lighting Control

Some survey studies indicate that photo-controlled lighting are not always successful in terms of user acceptance and satisfaction (Bierman & Conway 2000; Christoffersen and others, 1997; Doulos and others, 2007; as cited in Granderson et al., 2010). Escuyer and Fontoynont (2001) conducted a qualitative study of the acceptability of lighting control systems in three sites with manual, semi-manual, and automatically controlled dimmable lighting, respectively.

They found that automatic dimming was acceptable for the occupants; however, manual dimming was more likely to produce conscious satisfaction. Occupants indicated that their preferred lighting control system is the one that allows them to chose and change the illuminance. Also, occupants do not like the automatic controls to switch the lights off, even when there is enough daylight.

2.6. THE CHALLENGES OF WINDOW SHADING DESIGN

The story of the San Francisco Federal Building's shading design is very instructive, as the project went through several retrofits to address issues related to glare and solar overheating (Konis, 2012). The initial facade design prior to occupancy

included floor-to-ceiling window wall with spectrally selective glazing (67% visible light transmittance and 37% solar heat gain). An outer layer made of perforated metal panels with 50% openness was installed on the southeast facade to provide additional solar control on this orientation. These panels can be tilted outward to provide unobstructed outdoor views. On the northwest facade, an exterior layer of translucent vertical fins was designed to control solar heat gain. The design was mainly based on thermal comfort analysis, and the only daylighting evaluation method used was the LEED Daylight and View criteria. LEED criteria does not take into account the effect of occupant control of shading devices, nor does it include any glare assessment.

Prior to occupancy, a research team from LBNL conducted an visual comfort assessment using high dynamic range imaging and concluded that occupants were likely to experience visual discomfort due to luminance contrasts, and direct view of the solar disc (Lee et al., 2006; as cited in Konis 2012). They recommended the installation of blinds or shades to help control glare. After the occupancy, in response to complaints from the occupants, interior roller shades (color = grey, openness =5%) were installed adjacent to the lower operable windows of both southeast and northwest facades. Since occupants still reported glare from southeast facade, the 5% openness roller shades on the southeast facade were replaced with 3% openness roller shades, and additional 3% openness roller shades were installed adjacent to the upper two sets of clerestory windows on the southeast facade. At the same time, the (0.67 VLT) glazing on the southeast facade was retrofit with a (0.24 VLT, 0.25 SHGC) solar control film, for a combined VLT of 0.16.

Considering the fact that occupants do not adjust the blinds frequently, these retrofits significantly affected the potential for electrical lighting energy reduction from photo-controls. The daylight sufficiency and view, intended in initial design, was also lost due to the added shading devices. Furthermore, the post-retrofits survey showed that a large percentage of occupants remained dissatisfied with lighting (23%) and visual comfort (35%). This problems could simply be avoided by using horizontal shading devices, e.g. light shelves, as it is the only solution that blocks the direct view of the solar disc without compromising the visual connection to outdoor.

2.6.1. The Benefits of Horizontal Shading Devices

Hua, Oswald, and Yang (2011) studied the performance of daylighting systems in a laboratory building. They found that horizontal shading devices are very effective in providing visual comfort and satisfaction with daylighting environment, and that vertical shading elements in east and west facade fail to create visual comfort for the occupants. They also indicated that a shading device that does not eliminate the view of the solar disc is not successful in glare control. Perforated aluminum panels and fabric shades are not able to completely control the glare.

There are a variety of daylight delivery systems used in side-lit rooms to provide shading by redirection sunlight. The simplest form of such device is a lightshlef. Several studies show that lightshelves perform well in providing ambient lighting (Benton et al., 1986; Molinelli & Boyer, 1987) and are able to improve the uniformity of daylight in a room (Littlefair, 1995), but their performance is affected by the ceiling geometry and height (Littlefair, 1995; Freewan, 2010), lightshelf reflectivity (Littlefair, 1995), and lightshelf slope (Kim, Shin, & Kim, 2005).

In comparison to many innovative daylight delivery systems for sidelit spaces, lightshelves have proven effective and reliable. Abdulmohsen, Boyer, and Degelman (1994) used scale model and computer simulation to study the performance of five different daylighting delivery systems for side-lighting: 1-lightshelf, 2-lightscoop, 3-prismatic panel, 4-holographic films, and 5- fixed mirrored louvers. They studied systems' performance under low solar altitude (30 degree) and the below average outdoor daylight availability. They found that the combination of an interior and exterior lightshelf was the most successful system in terms of adequate light levels, uniform daylight distribution, and reduction of discomfort glare in south facing windows.

Floyd and Parker (1998) evaluated the effect of lightshelves on the performance of a daylight-linked automatic dimming control system. They recorded power consumption and work-plane light levels in four identical private offices with the following shading configurations: 1- interior lightshelf with a white diffuse top, 2-interior lightshelf with a specular surface, 3- manually controlled horizontal blinds, and 4- window with no treatment. The greatest energy savings (46%) were achieved in the offices with interior lightshelves with a negligible difference between the two types of lightshelves. As expected, illumination levels were greatest in the office with no interior shading device but the lightshelves provided the best condition in terms of lighting uniformity.

Ochoa and Capeluto (2006) used Radiance simulation to compare three different conditions: a single window without any external protection, a horizontal lightshelf, and a basic anidolic concentrator mounted on the view window. They found that the anidolic concentrator provides the highest illuminance levels in the back of the room. However in

some solar angles the reflections of the concentrator caused glare. They concluded that the lightshelf provides a “safer” approach by reducing the contrast between the front and the back of the room, while sacrificing on illuminance levels. It is important to note that lightshelves can not prevent glare from the view window, thus the portion of the window below the lightshelf still needs a separate treatment to control glare (Almusaed, 2011).

2.7. GAPS IN THE LITERATURE

The reviewed literature mainly examined occupant shade and light control behavior in spaces with unsubdivided windows. The effect of a subdivided window on occupants’ use of shades and electric lighting has not been adequately studied. The few existing research that examined occupant use of blinds on subdivided windows concerned windows with identical shading devices on both parts of the window. Research is required on subdivided windows that feature mixed shading devices.

In addition, the previous research focused on environmental factors affecting the lowering of the shades, while few studies have deliberated on the factors influencing the raising of the shades. Moreover, most of the studies observed occupants’ shade and electric lighting control behavior separately; while Occupant use of electric lighting is very much related to occupant use of blinds and these two matters can not be studied independently.

It was mentioned in the literature that a daylight redirection system may work effectively with manual lighting controls, and that horizontal shading is more successful in glare control. There have not been enough field studies concerning energy saving potential of daylight control systems that incorporate horizontal shading in spaces with manual lighting controls.

CHAPTER 3
Subdivided Windows and Occupant Use of Blinds

This chapter studies the effect of a subdivided window on occupant use of blinds and electric lighting. The literature review revealed that occupant use of interior shading devices is one of the most influential factors in the admission of daylight into the buildings. It was also concluded that providing the occupants with adequate control over their environment is a key aspect of a productive workplace. This study examines whether a subdivide window can increase occupants' chance of opening the blinds, while maintaining their satisfaction and comfort.

3.1. INTRODUCTION

As discussed in the previous chapter, the occupants' control of shades in commercial and educational buildings negatively affects the potential for energy savings from daylight. Based on a number of observations, occupants don't adjust shading devices frequently, and once lowered, the blinds are left in place for days or even weeks leading to reduced daylight inside the spaces. There have been a few field studies identifying the factors that affect the operation of the shades. The majority of these studies focus on environmental conditions such as vertical solar irradiance at the window, direct solar penetration, and maximum or average window luminance (Rubin, Collins, & Tibbott, 1978; Rea, 1984; Lee & Selkowitz, 1995; Foster, Oreszczyn, 2001; Reinhart & Voss, 2003; Inkarojrit, 2005; Mahdavi, et al., 2008; Konis, 2011). The findings of these studies have been used to generate shade control behavioral models that help predict the energy saving potential of daylighting in side-lit workplaces (Lee & Selkowitz, 1995; Reinhart & Voss, 2003; Inkarojrit, 2005; LEED, 2012).

Although the current shade control behavioral models are able to predict shade lowering events based on indoor environmental conditions, they fail to provide realistic criteria for shade raising events. This might be due to the fact that shade raising events do not correlate directly with the same physical stimuli that affect the shade lowering events. Rather, the shade raising events seem to be affected by psychological factors, such as the comfort of co-workers and the occupants' interest in energy reduction, as well as the accessibility and ease of control of shading devices. Since occupants do not usually favor the automatic shading controls (Bordass, Bromley, & Leaman, 1993; Stevens, 2001; Inkarojrit, 2005), a successful daylighting design relies on finding the conditions that increase occupants' chance of raising the shades.

3.2. RESEARCH METHOD

An open plan studio space at the School of Architecture and Urban Planning, University of Wisconsin-Milwaukee was selected as the case study (Figure 3.1). This setting was selected because it had the potential to be a well-daylit space with windows that extend to the ceiling and a narrow floor plan, while the window shading design was merely the most economic solution available.

The room is located on the 4th floor of the 4-story building and measures 12.2 by 24.4 meters with windows facing south, west and north (Figure 3.2). The double-glazed clear glass windows measure 2.4 by 2.7 meters and have a visible transmittance of 73%. There are 40 workstations with computers in this room. The occupants were sophomore architecture students who occupied the space during the spring 2012 semester. For this study, the room was divided into two sections along the south-north axis: The subdivided window zone and the original window zone (Figure 3.3).

Fig. 3.1: An interior image of the studied room.

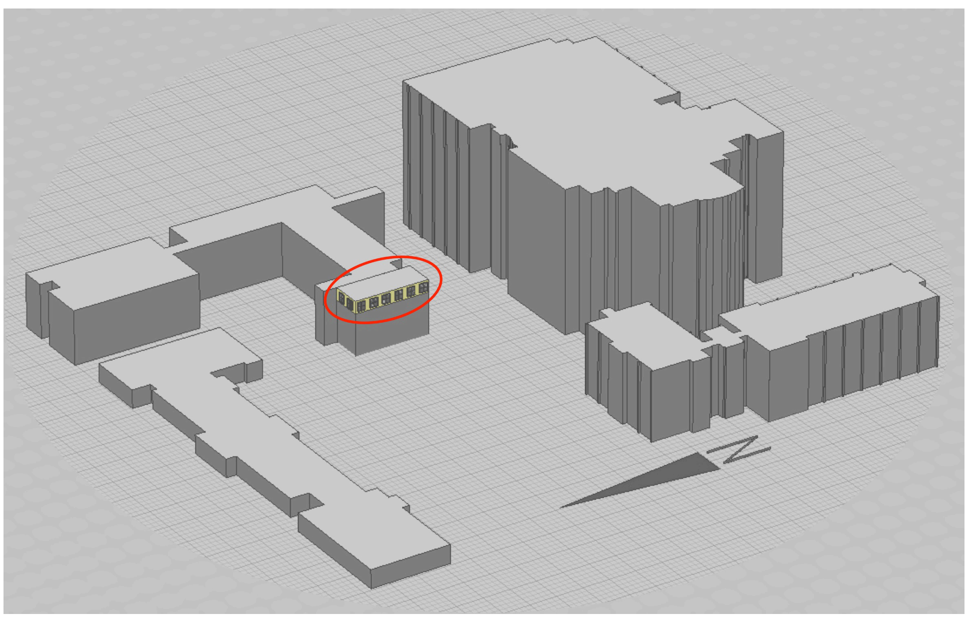


Fig. 3.2: The location of the studied room in relation to neighboring buildings

The original windows in the room have no fixed shading. They have manually controlled venetian blinds installed at the window head. In the subdivided window zone, first the existing venetian blinds were relocated to the middle of the window height. Then interior fixed louvers were installed on the upper half of the windows (Figure 3.4). This

configuration was selected based on the window design recommendations that suggest windows be subdivided into an upper “daylight” section and a lower “vision” section. The upper louvers were installed in varying angles, from 45 degrees at the middle of the window to 0 degrees at the top. The louvers were constructed with translucent white plastic panels, readily cut in 0.4 by 1.4 meter pieces. The benefit of a translucent shading material is that it introduces some diffused daylight while blocking the direct sunlight on work planes.

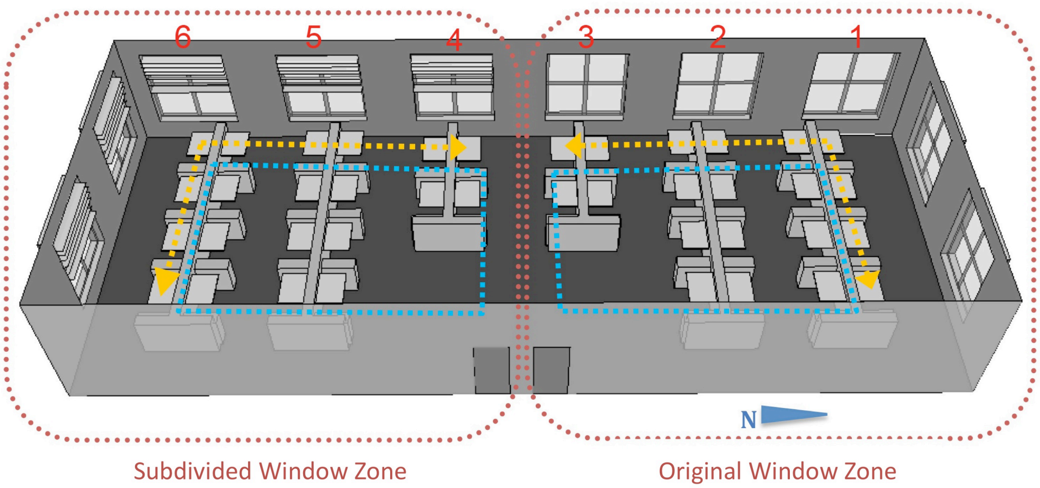


Fig. 3.3: The room was divided into two sections: The subdivided window zone, and the original window zone. The yellow arrows mark workstations at the perimeter whose occupants mainly control the blinds. The blue dotted lines mark the workstations at the core area.

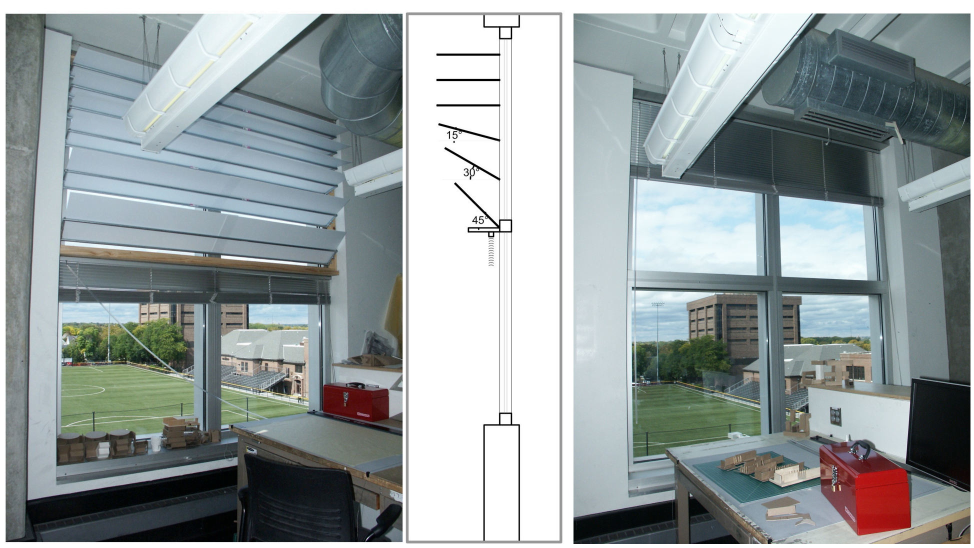


Fig. 3.4: The Subdivided window design (left) and the original window design (right)

3.2.1. Monitoring Occupant Use of Blinds on West Facing Windows

Occupant shade control behavior was monitored by photographing the west façade from April 3rd, to May 9th, 2012. The 6 windows on the west façade of the room consisted of 3 subdivided windows and 3 original windows (Figure 3.5). Assuming that all of these windows receive identical amounts of solar radiation, the question was whether the occupants of the two zones would use their venetian blinds in the same manner. The photographs were taken twice per day in the mid-morning and mid-afternoon. This timing was selected based on the previous field studies showing that occupants do not operate the shades on an hourly or even daily basis (Rubin, Collins, & Tibbott, 1978; Rea, 1984; Foster, Oreszczyn, 2001; Inkarojrit, 2005; Konis, 2011).

Fig. 3.5: The west façade of the building. Windows 1, 2 and 3 are original windows. Windows 4, 5, and 6 are subdivided windows.

After acquiring the images, the window occlusion index for each window was calculated using Foster and Oreszczyn's (2001) method: "The blind position value ranges

from 0 to 10 (0=fully open, 10= fully closed) and the slat angle value ranges from 1 to 3 (1=horizontal, 2=between horizontal and vertical, 3=vertical). Both values are divided by their maximum value to obtain the proportion of occlusion. The occlusion index is calculated by multiplying the blind position and the blind slat angle values".

3.2.2. Monitoring Occupant Use of Electric Lighting

In the studied room, the electric lights are controlled by 4 manual on/off switches at the door (two switches per zone). At each zone, one of the switches controls two rows of fluorescent luminaries by the west windows, and the other one controls the rest of the luminaries. To monitor the electric light usage, 4 HOBO U12 data loggers were installed next to selected fluorescent lamps each representing one switch. The HOBO data loggers recorded the illuminance levels at 5-minute intervals to identify the light switching events. The data was gathered from February 23 to May 16, 2012 (84 days). The room is occupied every day from 8 am to 11pm. To compare the electric light usage in the subdivided window zone with that in the original window zone, the number of the hours when the lights were turned on between 9 am and 5 pm was calculated for each zone

3.2.3. Occupant Satisfaction Survey

A survey questionnaire was distributed among the occupants twice during the study to examine their view on their visual environment. The occupants filled the questionnaire once on March 12th, 2012 under overcast sky condition, and another time on May 9th, 2012 under partly cloudy sky condition. Beside the multiple choice questions, the survey allowed the occupants to include their open comments on the installed shading system. The complete survey questionnaire can be found at Appendix A.

3.3. THE RESULTS

3.3.1. Occupant Shade Control Behavior

Table 3.1 shows the overall occlusion of each window, which equals sum of occlusion indices divided by the highest occlusion possible. The highest possible occlusion means the window shades were kept closed the entire time during the observation period. The results from window 1 must be ignored, as an art installation on the window halfway through the observation period affected the use of blinds. As seen in table 3.1, the occupants who controlled the venetian blinds on the subdivided windows demonstrated lower window occlusion (20% to 41%) than the occupants in the original window zone did (65% to 70%). Since the environmental conditions, such as transmitted vertical irradiance, are equal on the entire west facing windows, the significant disparity in occupants' shade control behavior must have resulted from the difference in shading configuration.

Table 3.1: The overall occlusion values calculated for west facing windows

	Window Number	Overall Occlusion	Occlusion in the morning	Occlusion in the afternoon
Original Windows	Window 1	8%	0.0%	16.6%
	Window 2	70%	69.8%	69.4%
	Window 3	65%	65.7%	64.9%
Subdivided Windows	Window 4	20%	20.2%	20.2%
	Window 5	25%	24.6%	24.6%
	Window 6	41%	33.9%	48.6%

Figure 3.6 shows the occlusion index of the windows over the observation period. Similar to previous studies, the frequency of shade operation is low in all of the windows, and window configuration did not affect the frequency of operation significantly. However, venetian blinds in window 6 had the highest frequency of use compared to other windows. As a result, there is a more meaningful difference between the morning

and afternoon occlusion values associated with window 6 in table 3.1. It is important to note that on the original windows 2 and 3 the venetian blinds were never fully retracted and they were only moved within the lower half of the windows, while on the subdivided windows, occupants either fully retracted the blinds to its highest possible level (middle of the window) or kept the slats horizontal most of the time.

Figure 3.7 illustrates the correlation between the occlusion index and the sunshine index for each window. The sunshine index was calculated by multiplying the weather code (1=overcast, 2=slightly cloudy, 3=sunny) by time code (1=morning, 2=afternoon). The resulting correlation coefficients (r) range from -0.26 to 0.467, indicating a weak relationship between the sky condition and the use of the blinds in all of the windows.

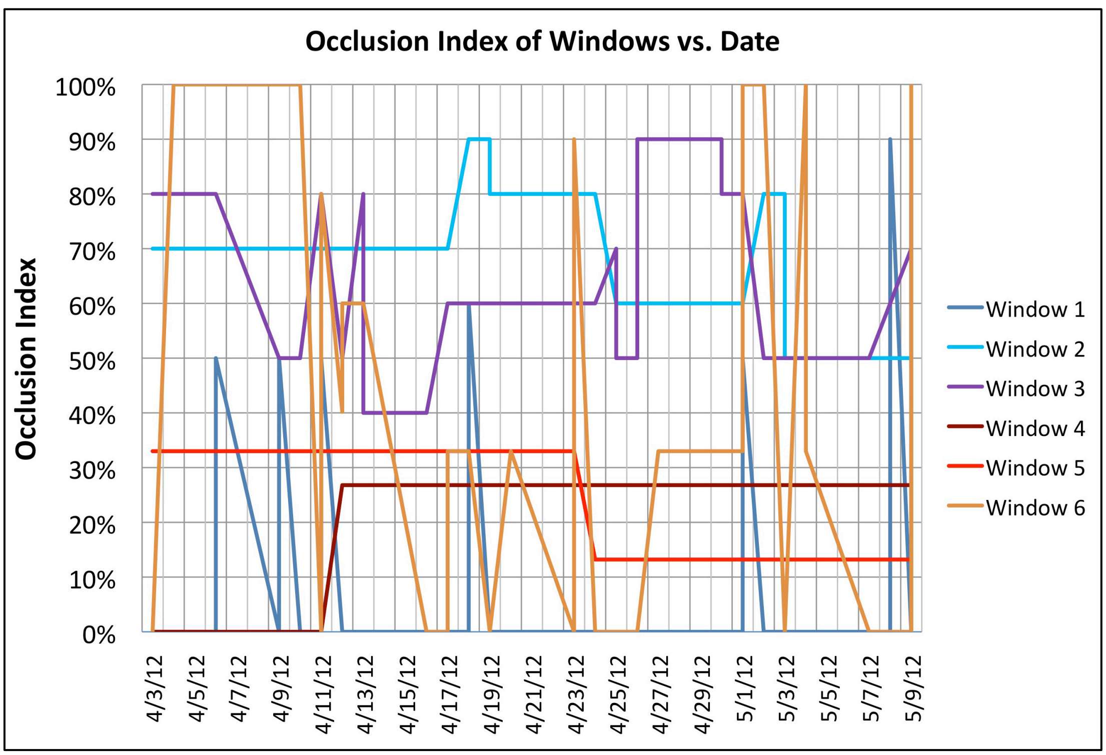


Fig. 3.6: The variation of the occlusion index of the windows per half-a-day. On average, occupants adjusted the blinds every couple of days. Windows 4 and 5 show the lowest frequency, and window 6 shows the highest frequency of use.

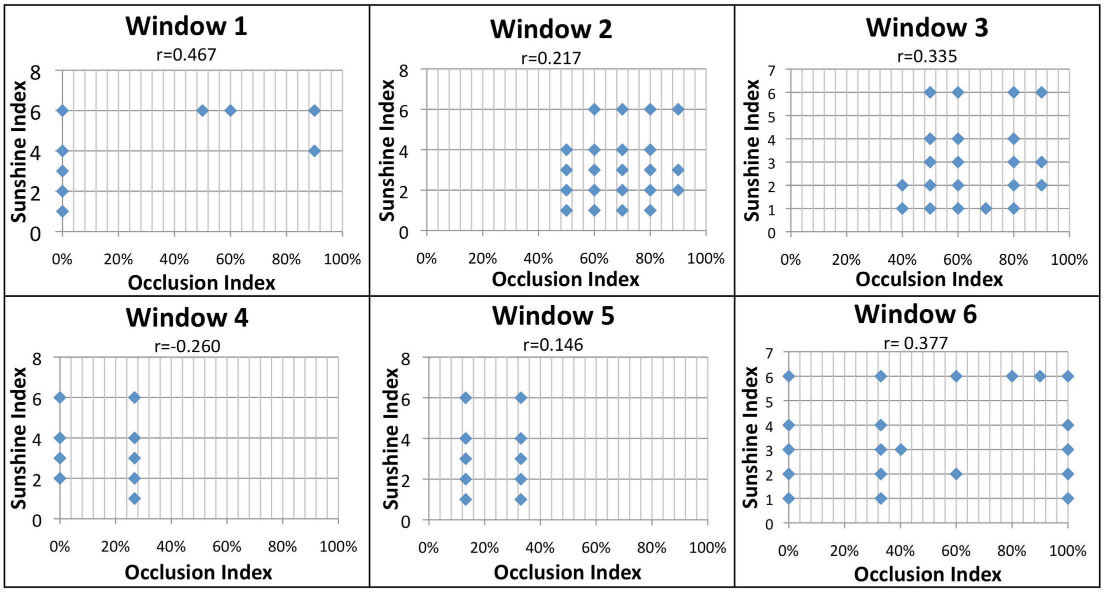


Fig. 3.7: The correlation between the occlusion index and the sunshine index. A sunshine index of 6 represents a sunny afternoon (maximum sunshine for west windows) and a sunshine index of 1 represents a cloudy morning (minimum sunshine for west windows).

3.3.2. Electric Light Usage

Table 3.2 shows the electric light usage during the observation period at each zone. It can be observed that the occupants in the subdivided window zone used 35-40 percent less lighting energy than the occupants in the original window zone. The correlation study between the sunshine index and the electric light usage revealed a weak relationship between the two variables (Table 3.3). Also no significant relationship was found between the window occlusion and use of electric lights in any of the windows (Table 3.4).

Table 3.2: Summary of lighting energy use from Feb 23 to May 16, 9am to 5pm.

Luminaries location	Number of hours when the lights were turned on between 9 am and 5 pm	Percent of the time when the lights were turned on between 9 am and 5 pm
Subdivided window zone - Perimeter	298 h	44%
Subdivided window zone - Core	326 h	48%
Original window zone - Perimeter	478 h	71%
Original window zone - Core	491 h	73%

Table 3.3: Correlation coefficients (r) between electric light usage and sunshine index.

Luminaries location	Correlation with Sunshine Index
Subdivided Window zone - Perimeter	0.06
Subdivided Window zone - Core	-0.06
Original window zone - Perimeter	-0.05
Original window zone - Core	-0.03

Table 3.4: Correlation coefficients (r) between electric light usage and window occlusion.

Luminaries location	Window 2	Window 3	Window 4	Window 5	Window 6
Subdivided Window zone - Perimeter	-	-	0.04	-0.07	-0.18
Subdivided Window zone - Core	-	-	0.08	-0.30	-0.11
Original window zone - Perimeter	-0.16	0.02	-	-	-
Original window zone - Core	-0.09	0.01	-	-	-

3.3.3. Survey Results

The survey data from both groups of occupants were processed and analyzed in order to verify the impact of the subdivided window on occupants' satisfaction. The results are illustrated in graphs and tables as follows. Figure 3.8 displays the time distribution of the occupants' activities in their workstations. On average, occupants spend almost 50% of their time in the studio on working with computers.

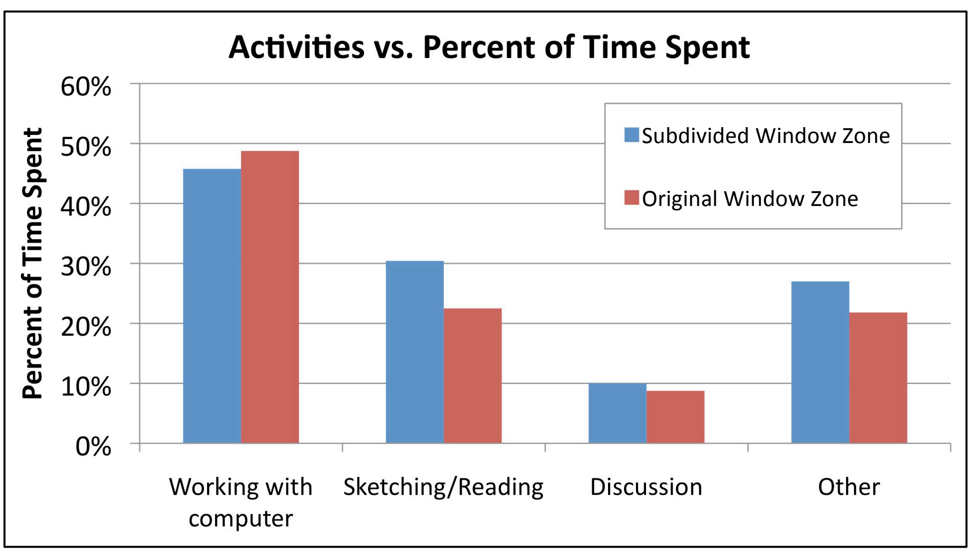


Fig. 3.8: The proportion of the activities in the room.

Figures 3.9 and 3.10 show occupants' rating of different aspects of their visual and thermal environment in March and May respectively. In March, the participants in the original window zone (N=12) were slightly more satisfied with most of the factors in question compared to the participants in the subdivided window zone (N=13). However, visual comfort and daylight distribution were ranked somewhat higher in the subdivided window zone than in the original window zone. In May, the trend was reversed and the participants in the subdivided window zone (N=16) indicated slightly higher level of satisfaction with all of the visual environment factors compared to those in the original window zone (N=12).

A two–tailed unequal variance t-test (α=0.05) was performed in each category to investigate the significance of difference between the means of the two groups (Table 3.5). The t-test revealed no significant difference between the subdivided window zone occupants and the original window zone occupants' satisfaction level with different aspects of their visual environment. In other words, the subdivided window did not remarkably affect occupants' opinion about their visual environment.

Table 3.5: The *p*-values calculated from the t-test (α=0.05).

	Amount of electric light	Amount of daylight	Distribution of daylight	Distribution of electric light	Amount of light for computer task	Amount of light for paper-based task	Amount of control over electric lighting	Amount of control over daylight	The access to view out	Visual comfort	Thermal comfort
March	0.291	0.954	0.573	0.436	0.327	0.409	0.817	0.114	0.685	0.575	0.339
May	0.374	0.841	0.122	0.641	0.449	0.385	0.172	0.323	0.976	0.080	0.868

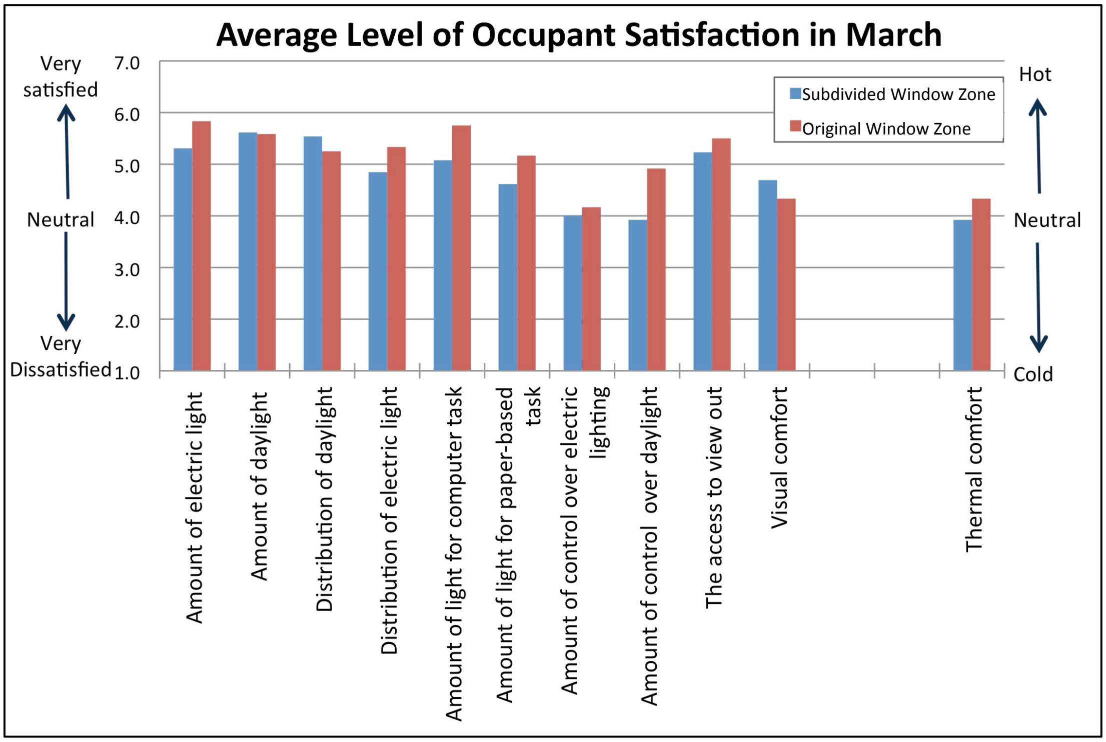


Fig. 3.9: The average level of occupant satisfaction in March.

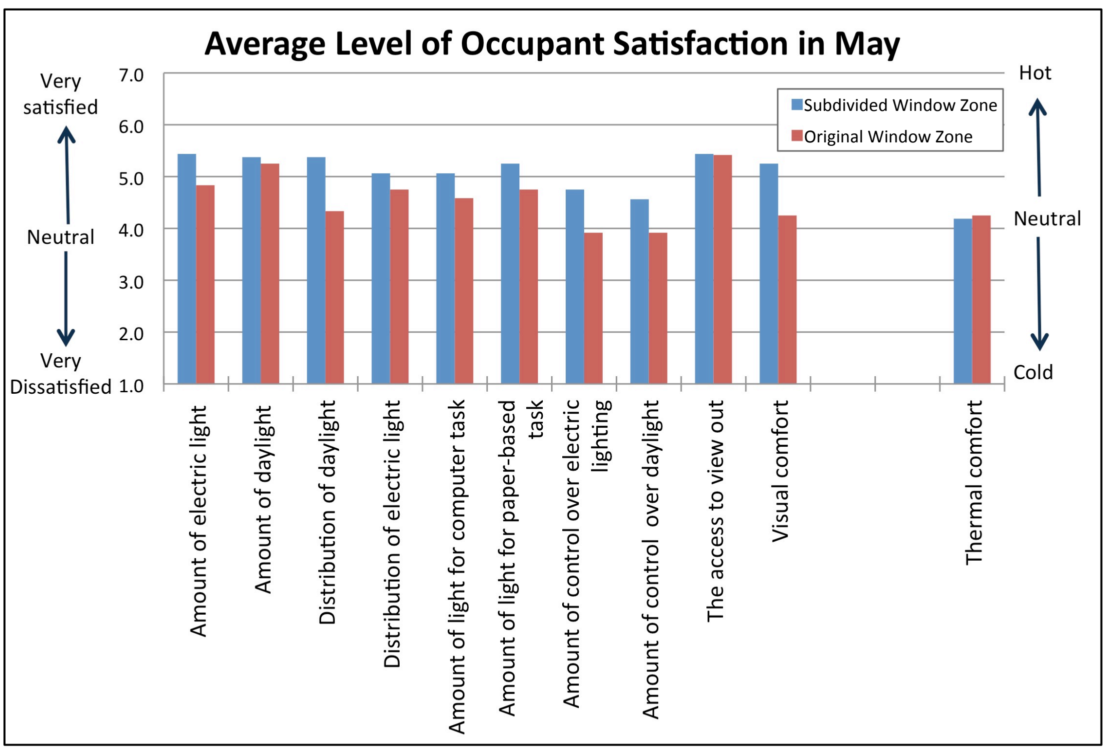


Fig. 3.10: The average level of occupant satisfaction in May.

The next section of the survey looked more deeply into the causes of dissatisfaction with the visual environment. Each zone this time was subdivided into a perimeter and a core area. This provided an opportunity to identify the problems of the occupants in the perimeter area separately from those of the core area occupants. Figures 3.11 and 3.12 display factors contributing to occupants' dissatisfaction with their visual environment in March and May respectively.

The March survey data shows that the occupants located in the perimeter of the subdivided window zone mainly complained about the glare from windows (71%), blinds being hard to operate (57%), and reflections from daylight on computer screens (43%). Whereas, in the core area of the subdivided window zone the major causes of dissatisfaction were not having enough view out (33%) and glare from windows (33%).

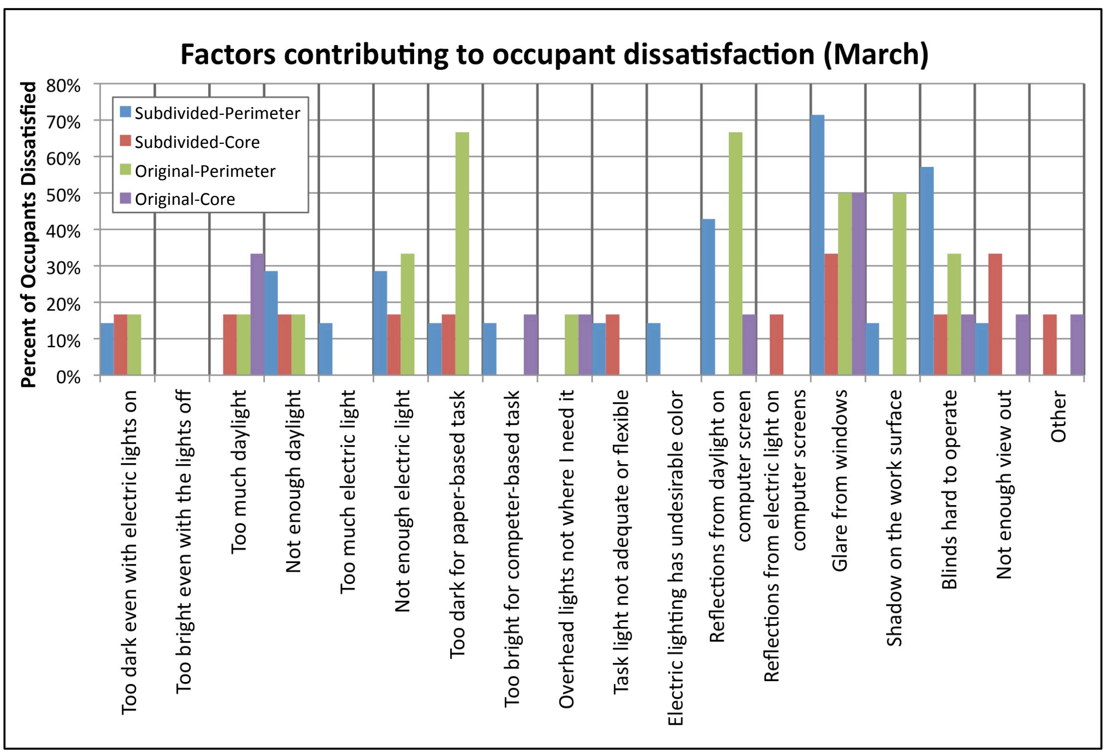


Fig. 3.11: Factors contributing to occupants' dissatisfaction with their visual environment in March.

In the perimeter area of the original window zone, occupants indicated that reflections from daylight on computer screens (67%), the room being too dark for paper-based tasks (67%), glare from windows (50%), and shadows on the work plane (50%) mainly contributed to their dissatisfaction with their visual environment. Finally, in the core area of the original window zone, glare from windows (50%) and too much daylight (33%) were major problems.

In May, the occupants of the perimeter of the subdivided window zone complained about the same factors as they did in March, however blinds being hard to operate ranked first this time (70%). In the core area of the subdivided window zone, not having the view out was still the major issue (33%), but fewer occupants were dissatisfied with the glare from windows (17%) compared to March. In the perimeter area of the original window zone, there was an increase in the number of the occupants

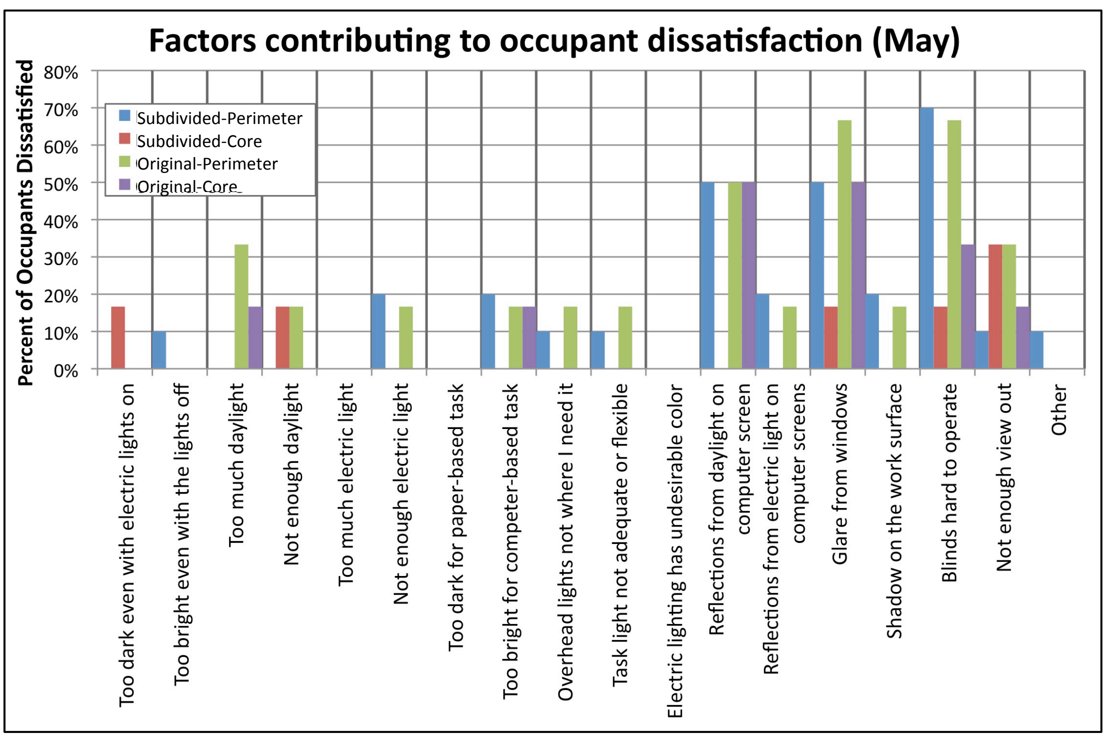


Fig. 3.12: Factors contributing to occupants' dissatisfaction with their visual environment in May.

dissatisfied due to blinds being hard to operate (67%) and glare from windows (67%). However, the room being dark for paper-based tasks was not an issue anymore.

In the core area of the original window zone, occupants this time complained more about reflections from daylight on computer screens (50%), and glare from windows (50%) was still an issue. In general, both surveys indicate that blinds being hard to operate and the glare from windows are the main disturbing factors in both zones, especially in the perimeter.

The subsequent questions in the survey concerned occupants' attitude toward raising and lowering the venetian blinds. Figures 3.13 and 3.14 show the occupants' primary reasons for lowering/closing the venetian blinds in Mach and May respectively. Most occupants in all areas indicated that reducing glare from windows is their primary reason for lowering/closing the blinds. However, a significant number of the occupants in the perimeter area of the original window zone indicated that they lower the blinds to eliminate the reflections on their computer screen (67% in March and 83% in May).

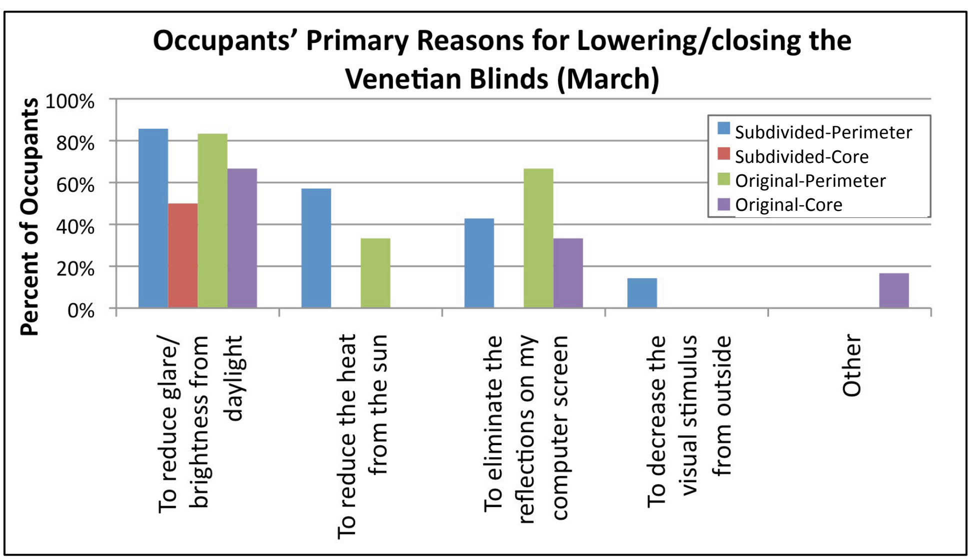


Fig. 3.13: Occupants' primary reasons for lowering/closing the venetian blinds in March

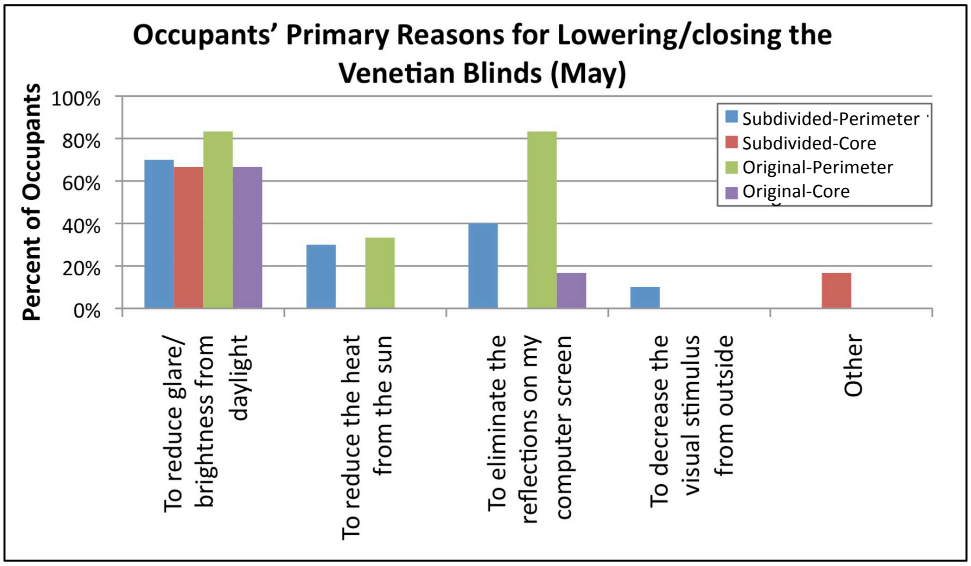


Fig. 3.14: Occupants' primary reasons for lowering/closing the venetian blinds in May

Figures 3.15 and 3.16 describe occupants' primary reasons for opening the blinds in March and May. The majority of the occupants mentioned that their primary reasons for raising/opening the venetian blinds were to increase the level of daylight in the studio and to maintain visual contact to the outside. Figures 3.17 and 3.18 summarize occupants' responses to the question "what are your primary reasons for NOT raising/opening the venetian blinds when the disturbing factors are eliminated".

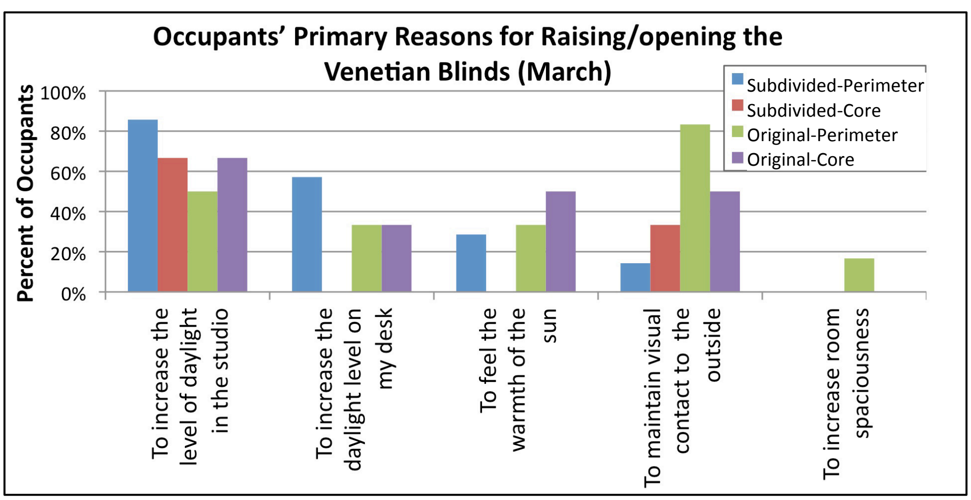


Fig. 3.15: Occupants' primary reasons for raising/opening the venetian blinds in March

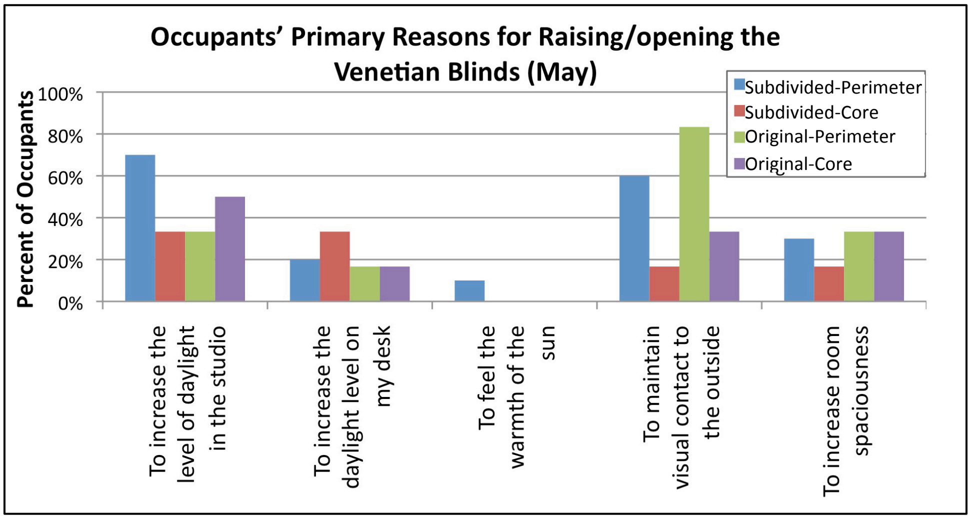


Fig. 3.16: Occupants' primary reasons for raising/opening the venetian blinds in May

Occupants in the subdivided window zone's perimeter area mainly blamed blinds being hard to operate for not raising the blinds both in March and May. The core area occupants in that zone, however, mentioned they try to avoid complains from other students (March) and they are too busy to adjust the blinds (May). In the original window zone, the perimeter occupants indicated that they don't want to disturb the class (March) and the blind control is not easy to access (May). Whereas the core area occupants did not emphasize on a particular reason and provided a wide variety of responses.

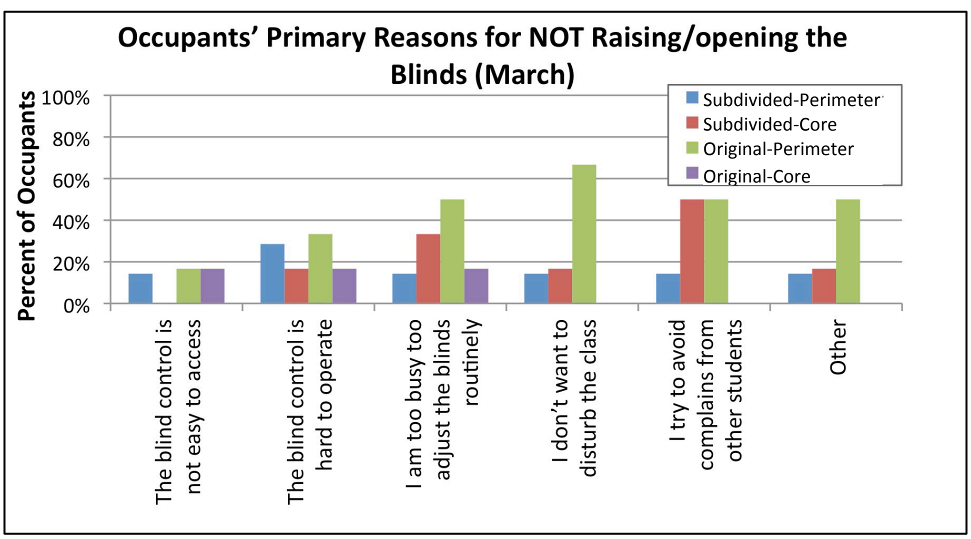


Fig. 3.17: Occupants' primary reasons for NOT raising/opening the venetian blinds when disturbing factors are eliminated in March.

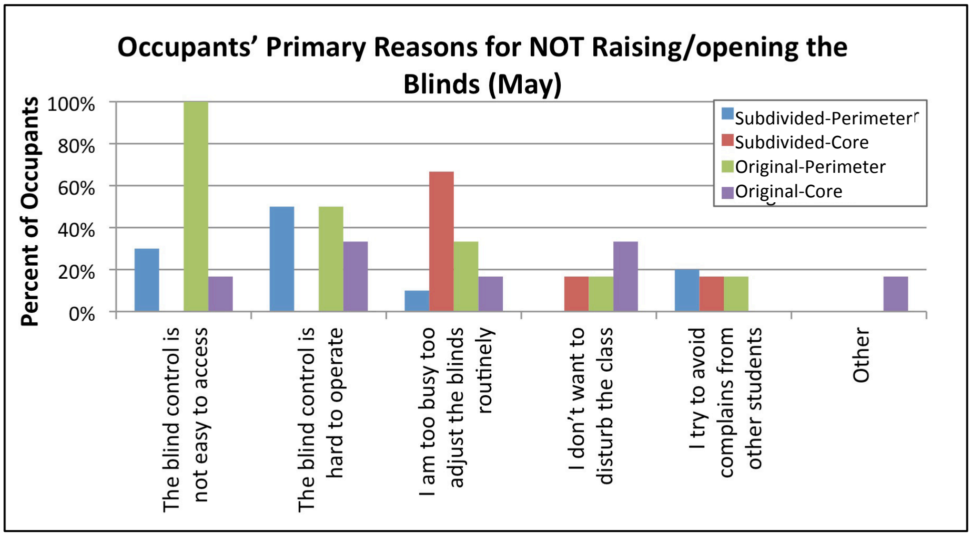


Fig. 3.18: Occupants' primary reasons for NOT raising/opening the venetian blinds when disturbing factors are eliminated in May.

At the end of the survey, the occupants of the subdivided window zone were asked to openly comment on the installed shading system. The following are some of their comments:

- An occupant located at the perimeter of the subdivided window zone indicated that he had spent a semester in this room before the installations, and shade control was problematic, because the core area occupants preferred the shades to be open, while the perimeter occupants experienced discomfort. He indicated great satisfaction with the new system with which he could freely adjust the venetian blinds without fearing complains from other occupants. He also mentioned that occupants in the original window zone showed interest in the system and wished to have them installed on their side of the room.
- Another occupant located at the core area of the subdivided window zone complained about his lack of control over the shading devices. He also mentioned he preferred an operable louver system.

- A perimeter area occupant pointed that some direct sunlight entered the room through the corners of the louver system at times.
- A core area occupant indicated that the upper louvers blocked his view out and made the room on their side look smaller.

3.4. DISCUSSION AND CONCLUSION

This study investigated the effect of a subdivided window on occupant use of blinds and lighting energy. The subdivided windows featured fixed louvers on the upper half and occupant-controlled venetian blinds on the lower half of the windows. The control group in this study was occupants located within a conventional window zone with venetian blinds installed at the window head.

The results demonstrate that on average subdivided windows provided 2 hours less electric light usage per day, without a significant difference in occupant satisfaction. The window occlusion data in this study suggests that when occupants are given full control over the view part of their adjacent windows they raise the shades more often; however the data does not provide a clear reason for this behavior.

The façade observations in this study also revealed that even in conventional windows occupants moved the venetian blinds only within the lower half of the window and never completely retracted the blinds, probably minding other occupants comfort. In a previous research on subdivided windows with fabric shades occupants adjusted the lower shades more often than the upper shades (Konis, 2011). These outcomes suggest that a subdivided window in which the occupants only control the blinds in the vision section (lower part) of the windows may produce better daylight condition and energy savings compared to the unsubdivided windows.

The only problem with the studied shading system was that the fixed louvers in this research caused low levels of daylight on overcast days. Figure 3.19 shows workplane illuminance levels measured using a LiCor Photometer in both zones under overcast sky condition. This issue was also raised by some of the occupants who showed interest in a dynamic system rather than the fixed louvers.

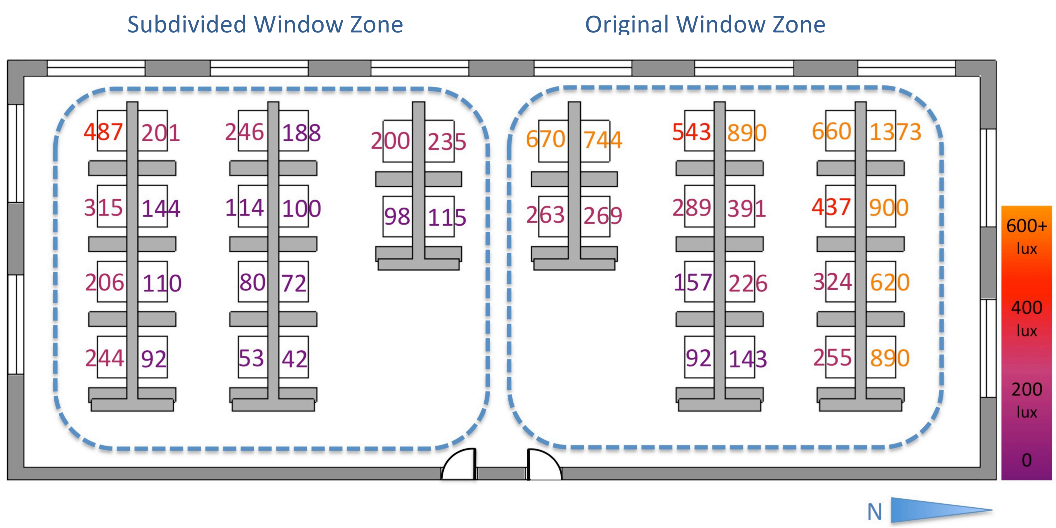


Fig. 3.19: Illuminance levels (lux) on workplanes measure under overcast sky condition (Global illuminance =15000 lux). Electric lights add about 320 lux to these values.

However, most of the current automatic shading devices, including motorized roller shades and switchable windows, block or limit daylight and the view out when activated. Therefore a redirecting shading system such as dynamic louvers seem more appropriate on the upper section of the subdivided windows. In such system, the activated shades will block the direct sunlight but admit the indirect daylight into the space, allowing the lighting controls to dim the electric lights in sunny days. A dynamic louver system will also presume some of the view out for core area occupants through the space between the louvers.

Another important lesson learned from this research is to provide a shading control that is smooth and easily accessible for the occupants. Based on the survey results, blinds being hard to operate was described as a major factor in occupants' infrequent use of the blinds. Also, moving the perimeter workstations slightly away from the windows will eliminate the lack of control for the core occupants, as it provides an opportunity for them to reach to the windows and control the blinds as needed. This strategy will also reduce the perimeter occupants' perceived glare, leading to lower deployment of the shades.

CHAPTER 4
Daylight Performance Metrics

In previous chapter, the benefits of a subdivided window were discussed. This chapter introduces the daylight performance metrics used to evaluate a variety of subdivided windows in the next two chapters. It provides an overview of the current metrics and validates the glare metric selected for the visual comfort assessment of the design options.

4.1. DAYLIGHT SUFFICIENCY METRICS

Unlike thermal comfort, there is not a holistic assessment method for predicting the quality of luminous environment (Veitch & Newsham, 1995; Osterhaus, 2005). As Miller (1998) describes it, the current approach to lighting design is a "recipe" containing disparate control metrics as ingredients to ensure satisfactory illumination in spaces (Osterhaus, 2005). Some of these metrics control the presence of adequate daylight for task performance, some evaluate the distribution of daylight in the space, and others assess the visual comfort of the occupants. In each category there are a number of different metrics to be used.

Among daylight sufficiency metrics, daylight factor and instance illuminance (illuminance level at a certain date/time) are the oldest and most familiar. Although these metrics, also known as static daylight metrics, are helpful in quick and primitive evaluation, they bear a few shortcomings. For instance, daylight factor calculated with CIE overcast sky model is intended only for worst-case scenario assessment, and it is not sensitive to window orientation and location. The new climate-based metrics provide better understanding of the annual daylight condition in a space.

4.1.1. Dynamic Daylight Performance Metrics

With the development of the annual daylight simulations, a number of new metrics have emerged. These metrics, known as dynamic daylight metrics or climate-based daylight metrics, are obtained through the post-processing of the annual illuminance profiles. Since in annual daylight simulation TMY (Typical Meteorological Year) weather data is used to create hourly sky models, dynamic metrics are more specific to the building location. Also, these metrics demonstrate buildings' daylight performance under all sky conditions rather than a few selected skies. Table 4.1 shows a number of dynamic daylight metrics and their definition. In this dissertation three metrics of UDI, DA and DAmax are used to evaluate daylight sufficiency in the spaces.

Table 4.1: Dynamic daylight performance metrics

Metric	Proposed by	Definition
Daylight Autonomy (DA)	Reinhart and Walkenhorst (2001)	The percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone.
Useful Daylight Illuminances (UDI)	Mardaljevic and Nabil (2005)	The percentage of the occupied times of the year when daylight level is between 100 and 2000 lx.
Continuous Daylight Autonomy (DAcon)	Rogers (2006)	Same concept as DA with the difference that DAcon gives partial credit to time steps when the daylight illuminance is below the user defined threshold.
Maximum Daylight Autonomy (DAmax)	Rogers (2006)	The percentage of the occupied hours when direct sunlight or exceedingly high daylight conditions are present. The excessive threshold is usually set as ten times the design illuminance of a space.
Annual Light Exposure	International Commission on Illumination (2004)	The cumulative amount of visible light incident on a point of interest over the course of a year. It is measured in lux hours per year, and is used for spaces that contain light-sensitive artwork.

4.2. VISUAL COMFORT METRICS

Visual comfort assessment metrics control the presence of glare in occupants' field of view. Current lighting standards are mostly based on visual performance rather than

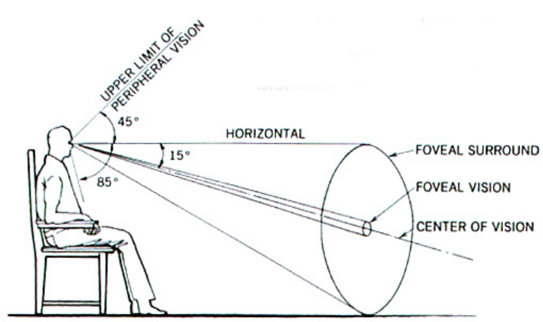
visual comfort (Osterhaus, 2005). However, the design community is shifting attention toward the visual comfort as key aspect of successful daylighting design. The following provides an overview of the current visual comfort assessment methods as well as a validation study of commonly used glare metrics.

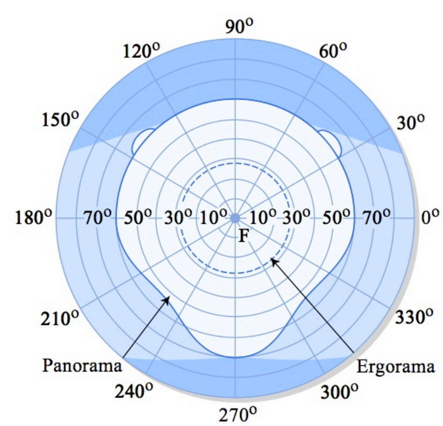
4.2.1. Glare Definition

In simple words, glare is defined as "unwanted light in the visual field" (Schiler & Shweta, 1997). Human eye can function quite well over a wide range of luminous environments, but does not function well if extreme levels of brightness are present in the same field of view. In the Lighting Handbook of the Illuminating Engineering Society of North America (IESNA, 2000) glare is defined as ''the sensation produced by luminance within the visual field[1] that is sufficiently greater than the luminance[2] to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility'' (p. G-15).

---

[1] The visual field is bounded by a cone of approximately 140 degree apex. In the center, a zone bounded by a cone of 1 degree apex is called the area of central vision, or foveal vision because light rays received from this area reach the retina on fovea. This area provides the most acute vision, and we instinctively move our gaze until the visual task falls exactly in this area. The build a sharp image of a larger portion of visual environment, our eye move rapidly around that direction. Typical VDT task takes about 10° to 30° of the central part of the visual field. The next zone is limited by a cone of 60 degree apex, and is called ergorama. The light rays from this area is received mostly by rods that make vision progressively blurred as we get further away from central vision. Panorama fills the outer part of the visual field. Its extend is limited by nose, cheeks and forehead. In this area objects are hardly noticed unless they move.





[2] The light energy leaving a surface in a particular direction is called luminance.

4.2.2. Current Glare Assessment Methods

Although many successful tools and methods have been developed to assess daylight performance of buildings, daylighting scholars are still not completely satisfied with the current glare metrics. The main problem in glare assessment is that glare is a subjective phenomenon affected by various aspects of human perception. Therefore, it is very difficult to create a direct link between the glare sensation as a subjective phenomenon and the objective and quantifiable parameters of the physical space. Studies even show that there are cultural differences in sensation of glare. For instance, Japanese are found to be more tolerant of glare compared to American or European subjects (Iwata et al., 1991; Iwata et al., 1992; Osterhaus, 2005).

Figure 4.1 represents a famous lightness illusion and forms the basis for glare sensation theories. The identical grey squares seem lighter in the dark background than in the white background. In other words, the absolute amount of light reflected from a surface (luminance) does not correlate with the perceived lightness of the surface. Researchers have tried to explain this illusion with eye adaptation theories. The dark surrounding makes your eye adapt to low light, so the same grey surface in this adaptation level seems brighter than that in the white surrounding.

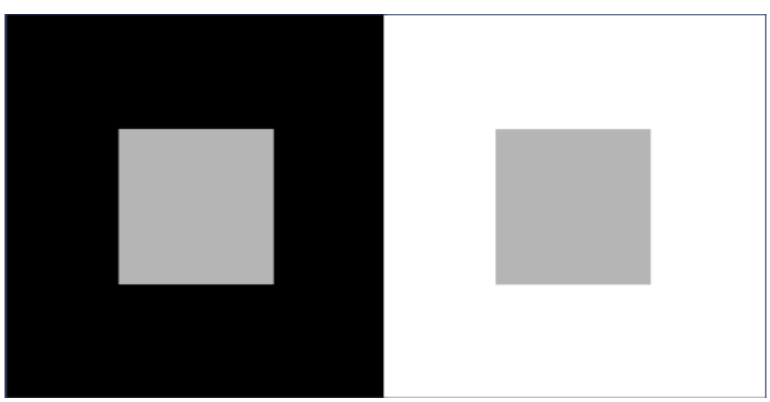


Fig. 4.1: Lightness perception illusion

4.2.2.1. Glare Indices

In daylit spaces, visual comfort is mainly affected by window luminance and luminance ratios within the field of view (Wienold & Christoffersen, 2006). Several attempts have been made to develop an equation that quantifies the subjective glare sensation based on window and space specifications. The main components of glare equations include brightness and size of the source, position of the glare source in the visual field and the eye adaptation[3] of the viewer (or background luminance) (Schiler & Shweta, 1997). The relationship between these parameters and glare sensation is generally expressed in variations of the following equation (Boyce, 1981; Osterhaus, 2005):

$$\textit{Glare}\ \text{sensation} = \frac{(\text{luminance of glare source})^{m} \times (\text{angular substanse of glare source at eye})^{m}}{(\text{luminance of background})^{x} \times (\text{deviation of glare source from line of sight})^{y}}$$

This equation suggests that the discomfort glare sensation increases with the luminance of the source and the solid angle subtended by the source, and decreases with increasing background luminance and deviation of the glare source from the line of sight. Luminance of background is also known as adaptation luminance. Glare can be avoided by providing a brighter background against which to view the source.

Most of the glare index equations are derived from experiments in which observers rank glare sources of different luminance levels according to the discomfort sensation they perceive. These experiments primarily were performed with electric light sources, and few equations have been proposed for discomfort glare of daylight origin (Chauvel et al., 1980; Chauvel and Perraudeau, 1995; Hopkinson, 1957, 1972; Hopkinson and

---

[3] Adaptation is the ability of the human visual system to adjust the sensitivity of the system, to the average level of light existing in a space. [1]

Bradley, 1960; Iwata et al., 1991, Nazzal, 2005). The glare indices known up to now for daylight and electric light include:

1- The American Visual Comfort Probability[4] (VCP)

2- The British Glare Index (BGI or IES glare index)

3- The European Glare Limiting (EGL)

4- The CIE Glare Index (CGI)

5- Unified Glare Rating system (UGR)

6- Daylight Glare Index (DGI)

7- Daylight Glare Probability (DGP)

The first three methods are only applicable to electric light sources mounted on the ceiling and they cannot predict glare from large sources of light or vertical sources such as windows (Osterhaus, 2005). The EGL method is no longer used since it is proven erroneous with current lighting systems including luminaires with specular louvers (Osterhaus, 2005). The CIE Glare Index (CGI) was developed by International Commission on Illumination (CIE) in an attempt to merge the best points of the major discomfort glare assessment methods of the time (CIE, 1983; Osterhaus, 2005). Its formula consists of two components, one describing the luminous environment of the room and the other computing the effect of luminance, size and position of the glare sources (Osterhaus, 2005).

The advantage of the CGI method to VCP and BGI methods is that this glare index takes into account the glare source contribution to the adaptation of the viewer's eye (Osterhaus, 2005). This is particularly beneficial when assessing large area glare sources

---

[4] This is a rating that expresses the discomfort glare in terms of the percentage of occupants who do not find the system uncomfortable.

in an observer's field of view, as a large source of glare, such as a window, will increase the adaption level of the eye, affecting the viewer's sensitivity to contrast (Osterhaus, 2005). However, the CGI method was also unsuccessful due to its complexity, limitations and regional character (Osterhaus, 2005). The CIE tried to reproduce a glare prediction system that would eliminate the weaknesses and retain the advantages of the previous systems, would be ''ultrasimple'', and be applicable in most countries (Osterhaus, 2005).

Consequently, they developed the Unified Glare Rating (UGR) system which is a simplified version of the CGI system (CIE, 1995). In UGR system, description of the luminous environment of the room is again reduced to the background luminance without inclusion of the effect of glare source in adaptation level (Osterhaus, 2005). This elimination once again made the UGR system suitable for electric light evaluation rather than daylight (Osterhaus, 2005).

To provide a suitable method to assess discomfort glare from daylight sources, Daylight Glare Index (DGI), also known as the ''Cornell Formula'', was developed by Hopkinson through laboratory tests on large area uniform glare sources (Hopkinson, 1963; Chauvel et al., 1982). Since observers demonstrated greater tolerance to mild degrees of glare from the sky seen through windows than to glare from electrically lit screens of comparable size (Chauvel et al., 1982), the Cornell Formula was modified slightly to take account of this daylight tolerance (Robbins, 1986).

$$DGI = 10\log_{10} 0.48\sum_{i=1}^{n}\frac{L_s^{1.6}\,\Omega_s^{0.8}}{L_b + 0.07\omega_s^{0.5}L_s}$$

L_b: Luminance of the background
L_s: Luminance of the glare source
ω_s: Solid angular subtense of source at the eye of the observer
Ω_s: Solid angular subtense of source modifies for the effect of the observer in relation to the source

Table 4.2: Glare sensation correlated to DGI in windowed laboratory

Degree of Perceived Glare	DGI
Just perceptible	18
Just acceptable	20
Borderline between Comfort and Discomfort	22
Just Uncomfortable	24
Just Intolerable	28

Despite the fact that DGI has been the accepted standard for many years, research has shown that its application can produce unreliable results. (Iwata et al., 1991 & 1992; Boubekri & Boyer, 1991). Waters et al. (1995) suggest that non-uniform glare sources are not covered by DGI method, as that index was developed based on data collected with uniform light sources (Osterhaus, 2005). In the absence of an alternative, however, the Daylight Glare Index remained the most widely used indicator for glare assessment.

Wienold and Christoffersen (2006) have recently developed a promising glare metric called Daylight Glare Probability (DGP). It represents "percent of people disturbed" and is based on human reactions to daylight-based glare in a side-lit office environment with venetian blinds. Like most glare calculations, finding DGP requires the size, position, and luminance of the source plus the vertical illuminance at the eye.

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log\left(1 + \sum_{i=1}^{n} \frac{L_{si}^2 \omega_{si}}{E_v^{1.87} P_i^2}\right)$$

E_v**:** Vertical illuminance at the eye
L_{si}**:** Luminance of the glare source
ω_{si}: Solid angle of the source
P_i: Position index of source

A number of studies have reported satisfactory results with DGP. For instance Jakubiec and Reinhart (2012) compared five glare metrics of DGI, CGI, VCP, UGR, and

DGP in terms of their ability to predict glare in three spaces under 144 clear sky conditions. They concluded that DGP was the most reliable method in glare evaluation and responded predictably to most daylight situations. Whereas, DGI predicted little glare from directly visible sun or a reflection, hence it should only be applied under conditions where direct sunlight is not present in the space.

4.2.2.2. Single Variable Criteria

Based on the brightness perception processes mentioned before, the Illuminating Engineering Society of North America (IESNA) suggests that surfaces of very different luminance not be placed next to each other in the field of view. When harsh contrast exists between the adjacent surfaces, the eye will have to constantly adapt while moving the gaze from one surface to another. This can cause disability in viewing the task, eye strain, and headache (IESNA, 1959). Accordingly, the Illuminating Engineering Society of North America (IESNA) recommends the following luminance ratios as a visual comfort criterion:

1:3 or 3:1	between paper and VDT task
1:3 or 3:1	between task and adjacent surfaces
1:10 or 10:1	between task and surrounding surfaces

Some researchers have proposed to use the averaged luminance of a window surface as a metric to evaluate glare from windows (Moeck's, 1998; Park, Augenbore, & Messadi, 2003). Currently, there is no clear-cut standard for limiting luminance on window surface, but IESNA RP-1 (1993) limits the luminance of any room surface to 850 cd/m2 (Park et al., 2003). In another research, the vertical illuminance measured near the facade and the average sky luminance measured from the back of the room were

found to be good measures to monitor visual comfort under intermediate and overcast sky conditions (Velds, 2002).

Van Den Wymelenberg and Inanici (2009) studied the effect of luminance distribution patterns on occupant preferences of daylit spaces and proposed that limiting the percentage of pixels that exceed 2000 cd/m2 in the field of view could be a useful criterion. They performed their study in a side-lit office space with venetian blinds, and obtained luminance distribution map of observers' field of view through HDR photography. Finally, Konis (2012) suggests that the maximum window luminance is a reliable visual comfort predictor, and must be maintained below 10000 cd/m2.

4.3. GLARE EVALUATION STEPS

4.3.1. Creating the Luminance Map

The first step in any glare evaluation is to create a luminance map. Traditionally, researchers relied on a handheld luminance meter as the primary method for documenting luminance distribution in field and laboratory studies. The photometric information gathered from the handheld device is a point-by-point measurement. While this method can be easily implemented, it has a few major disadvantages. First, in order to document luminance characteristics of a large surface area, the measurement session usually takes a long time to complete. In a daylit space where the environmental conditions change constantly, this can create systematic errors. Also, with a limited time to conduct the study in the field or in the laboratory, only a small number of data points can be collected at one time. Limited data points gathered from a large surface may be too coarse for a detailed analysis of luminance distribution.

To overcome the above-mentioned disadvantages, researchers have developed a new method to efficiently document luminance distribution with photography. The use of a camera to produce a luminance map was first proposed in the mid 1960s (Hopkinson et al., 1966). CCD cameras[5] have been applied in combination with a software which converts the camera signals into a luminance map (Berrutto and Fontoynont, 1995). For instance, the data gathered by a CCD camera is converted into a RADIANCE picture format (McHugh, Pande, Ander, & Melnyk, 2004). Then a Radiance-based software specifies the luminance value of each pixel in the image (Wienold & Christoffersen, 2006).

The weakness of this method is that the relation between the signal level and the resulting luminance value differs with shutter speed. In addition, there is a difference between the spectral sensitivity curve of the CCD camera and that of the human eye (Nazzal, 2005). An HDR (High Dynamic Range[6]) photography technique which involves collecting multiple exposure sequences is developed to address these shortcomings. In this technique luminance data is collected in a large (180° by 180°) field of view by a fisheye lens. Each exposure captures a different luminance range and the exposure sequences are assembled into one HDR image. The resultant HDR photograph is an accurate luminance map of the scene, where pixel quantities closely correspond with

---

[5] A charge coupled device (CCD) camera is an apparatus which is designed to convert optical brightness into electrical amplitude signals.

[6] The dynamic range is the ratio between the maximum and minimum values of a physical measurement. For a scene, dynamic range is the ratio between the brightest and darkest parts of the scene. Although Human eye can perceive a very wide range of luminances (10^{-6} cd/m^2 to 10^8 cd/m^2), it can not perceive the whole range simultaneously. Optic nerves can transmit signals of limited range. At any one time the perceptible range of luminance spans over three to four orders of magnitude between two thresholds: a lower limit below which no luminance sensation will be experienced, and an upper boundary above which glare sensation will occur. In other words, human eye can accommodate a dynamic range of approximately 10,000:1 in a single view. In CCD cameras, most 12-bit sensors have on average a dynamic range around 1,000:1 only. Standard display devices have a dynamic range of about 100:1. The Dynamic Range of real-world scenes can be quite high. Ratios of 100,000:1 are common in the natural world. An HDR image stores pixel values that span the whole tonal range of real-world scenes. Therefore, an HDR image is encoded in a format that allows the largest range of values, e.g. floating-point values stored with 32 bits per color channel.

physical quantities of luminance (in cd/m2) (Van Den Wymelenberg & Inanici, 2009).

4.3.2. Identifying the Glare Source

After acquiring the luminance map, the next step is to indentify the potential glare sources within the visual field of the observer. The human eye detects potential glare sources immediately, but in case of a picture evaluation, a detection algorithm is needed. Currently, there are three principal methods for the detection of glare sources:

1. *Scene average based luminance threshold:* The average luminance of the entire field of view is calculated and sections that are x-times brighter than the average luminance are counted as a potential glare source.

2. *Predetermined absolute luminance threshold:* A fixed value is determined as the threshold and sections higher than the fixed value are counted as a potential glare source.

3. *Task average based luminance threshold:* The average luminance of a given zone (task area) is calculated and sections that are x-times higher than the average luminance of this zone are counted as a potential glare source.

Wienold (2006) tested the three principal methods and concluded that the third method should be used since the first one fails to detect obvious sources of glare, and the second one does not take into account the eye adaption. Contrary to Wienold's findings, Van Den Wymelenberg and Inanici (2009) state that predetermined absolute thresholds provide a better glare detection criterion, because the glare sources detected by this method were more consistent with occupant reports in the field study.

4.3.3. Calculating the Glare Metrics

After identifying the potential sources of glare, different glare indices can be calculated by entering the brightness, location, and apparent size of the glare sources and

the background luminance into glare equations. As discussed earlier, DGP and DGI are mainly used with glare sources of daylight origin. There are a few software that automatically perform these tasks and provide the glare index values. For instance, Radiance's FINDGALRE tool detects the glare source based on the scene average luminance and Radiance's GLARENDX tool calculates a glare index of choice such as UGR or DGI. Another program called Evalgalre (Wienold, 2006) detects the glare source based on the user define criteria and calculates DGP, DGI, UGR, CGI, and VCP in one step. Other glare metrics such as the percentage of the pixels exceeding a threshold can also be calculated at this step.

4.4. A VALIDATION STUDY OF THE GLARE ASSESSMENT METHODS

The review of the current glare assessment methods revealed that there is not yet an agreed upon metric for glare evaluation. In addition, the validation studies have so far produced contrasting results. In order to select a glare metric for daylight performance assessment of the imminent subdivided windows, four glare metrics were tested in a daylighting design masterpiece. HDR images were captured at Alvar Alto's Mt. Angle Abby Library. The glare sensation degree was obtained for each image through DGP, DGI, IESNA-recommended ratios, and Pixel Percent methods. The validity of each method was decided based on the author's visual experience inside the space.

4.4.1. Mount Angel Abby Library by Alvar Alto

The Mount Angel Abbey Library is part of Benedictine Monastery located on the hilltop of Mount Angel, Oregon (Figure 4.2). It is the second architecture by Finnish architect Aalto in the United States after MIT dormitory in 1970 (Carbonnier, 2013). Although Mt. Angel Abby library has similar features to Alto's previous libraries in

Fig. 4.2: Mount Angel Abby Library

Finland, he mindfully adapted his design to the site of the building. He considered the sunpath as well as the protection of the natural vegetation in his design. An artistic combination of conical skylights, roof monitor and clerestory windows admit adequate amounts of daylight into the main library spaces (Carbonnier, 2013).

4.4.2. Capturing the HDR images

The HDR images were captured inside the library on Feb. 15, 2013. The sky condition was cloudy earlier in the morning and changed to clear sky at around noon. 12 exposure-bracketed images were taken at 8 selected viewpoints inside the building to represent the visitors' experience. The images were acquired using a Canon EOS 5D Mark II with an EF 8mm fisheye lens. The camera was fixed on a tripod at eye level of a seated or standing viewer based on the location of the image. Figures 4.3 and 4.4 display the imaging locations and their horizontal illuminance at work level. The luminance value of a grey card within the scene was recorded using a Gossen luminance meter in order to double check with the calibrated HDR images. The fstop was fixed at 5.6 and the shutter speed was changed from 4 seconds down to 1/500 seconds (Figure 4.5).

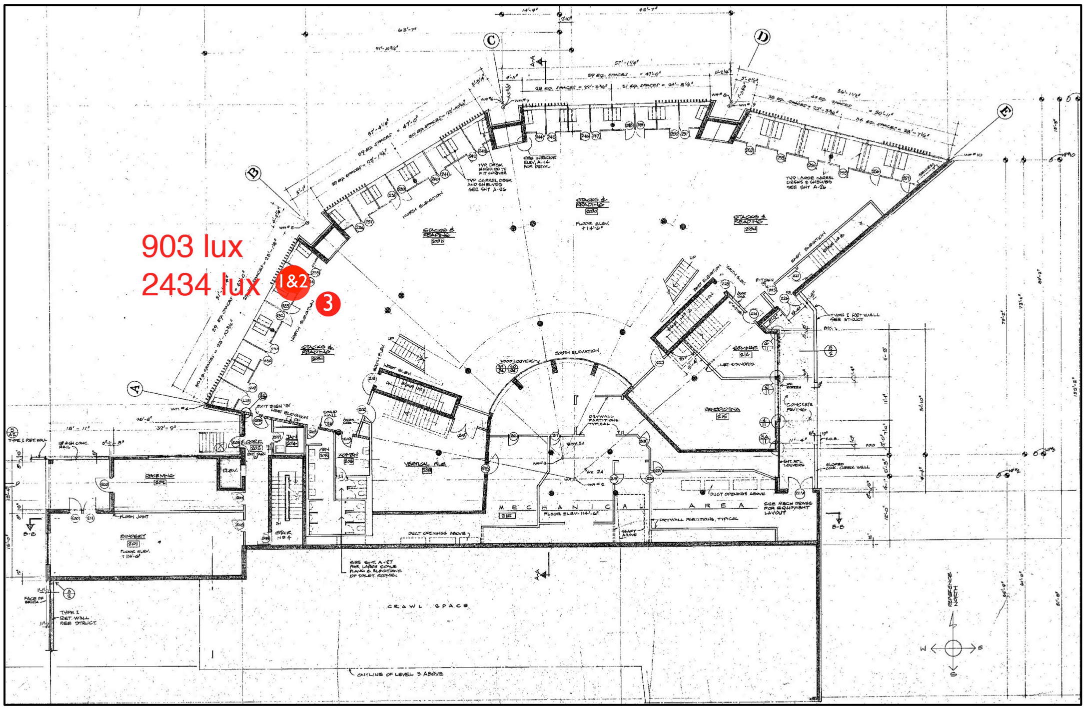


Fig. 4.3: Imaging locations at the lower level of the main library

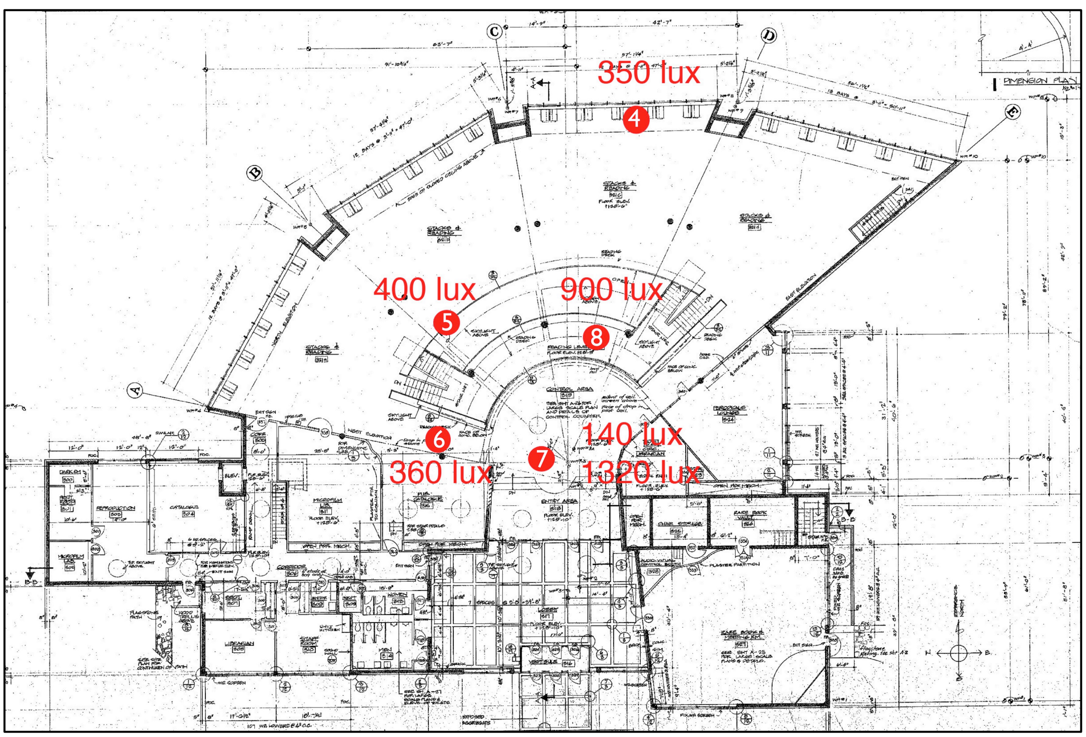


Fig. 4.4: Imaging locations at the upper level of the main library

Fig. 4.5: Exposure-bracketed images

The exposure-bracketed images were uploaded to Photosphere to compute the HDR images. The camera's response curve was computed and saved in Photosphere (Figure 4.6). It was used to calibrate the HDR images with actual scene luminances. The grey card luminance measurement at each scene helped to ensure that calibrated HDR images represented correct luminance values.

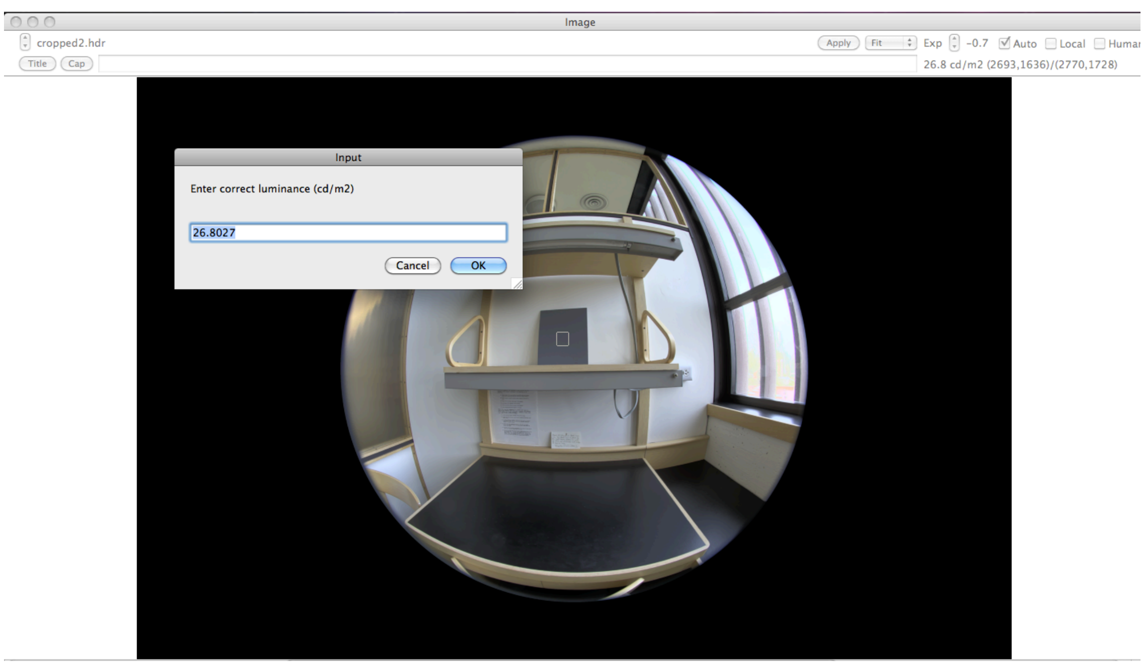


Fig. 4.6: Calibrating the HDR images

4.4.3. Vignetting Correction

The Canon fisheye lens uses equidistant projection to produce an image. The equidistant fisheye lenses exhibit noticeable light fall off (vignetting) from the optical axis toward the peripheral pixels. To have an accurate luminance map, it is necessary to address and correct this problem. First the vignetting function of the fisheye lens should be determined. The common method is to take HDR photographs under constant electric lighting in the absence of daylight. The camera is rotated with respect to the target in increments of 5 degrees until the camera field of view is covered (Figure 4.7).

At each increment a full HDR image is captured and the luminance of the target (usually a gery card) is determined from the HDR photograph (Inanici, 2006). Next, the luminance values of the grey card is transferred into Excel spread sheet in order to find the polynomial function representing the light fall-off pattern. Figure 4.8 illustrates the polynomial function derived for the aperture size of f/5.6. To correct the vignetting, the Radiance tool pcomb was used to implement the correction factor to each HDR image. The same tool was used to create a mask to clean up the images. The full procedure along with Radiance scripts is included in Appendix B.

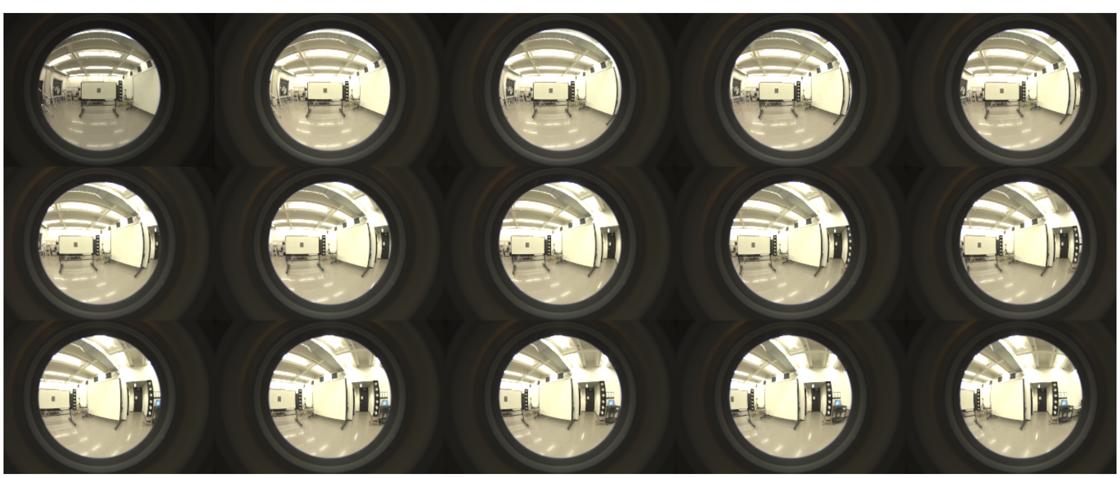


Fig. 4.7: HDR images of the target (grey card) at 5-degree increments.

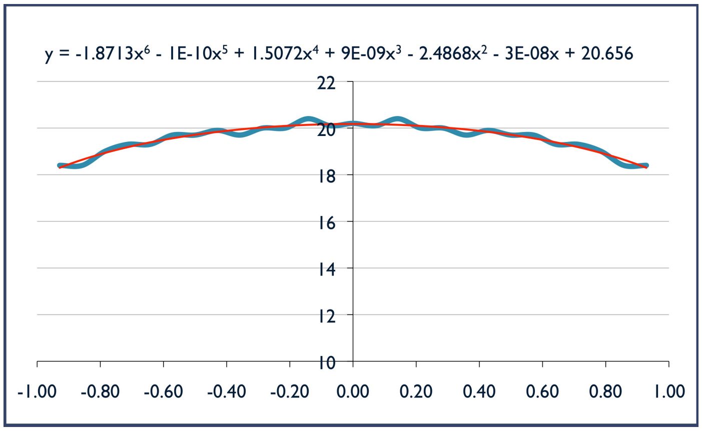


Fig. 4.8: Polynomial function representing the light fall-off in fish-eye lens with aperture size of f/5.6

4.4.4. Visual Comfort Assessment Using IESNA-recommended Luminance Ratios

Figures 4.9 to 4.16 show the ton-mapped HDR images of the interior views of Mt. Angel Abby library. The luminance values of selected pixels are printed on the image in order to assess the visual comfort using the IESNA recommendations. IESNA requires that the luminance ratio between adjacent surfaces not exceed 3, and the luminance ratios within the entire field of view not be greater than 10. As seen in figures 4.9 to 4.16, most of the surfaces display ratios higher than IESNA recommendation. Therefore, according to this method, occupants will experience discomfort in all of the studied locations.

4.4.5. Visual Comfort Assessment Using the Pixel Percent Method

As discussed earlier, the percentage of pixels that exceed 2000 cd/m2 in the FOV has proven to be a useful metric for glare evaluation (Van Den Wymelenberg & Inanici, 2009). In this method, a scene in which less than 10 percent of the field of view (FOV) exceed 2000 cd/m2 has no glare potential. Figures 4.17 to 4.24 show the HDR images in false color. In these images, yellow and light orange areas represent luminance values of 2000 cd/m2 or higher. According to this method of evaluation, glare sensation may only occur in view 1 and the rest of the scenes are glare free.

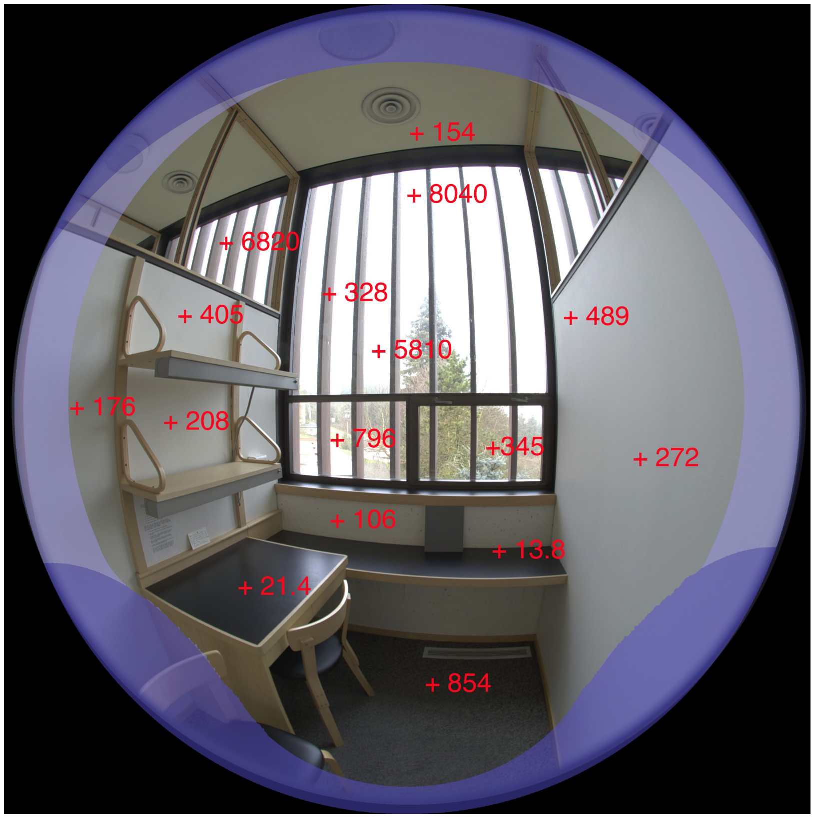


Fig. 4.9: View 1

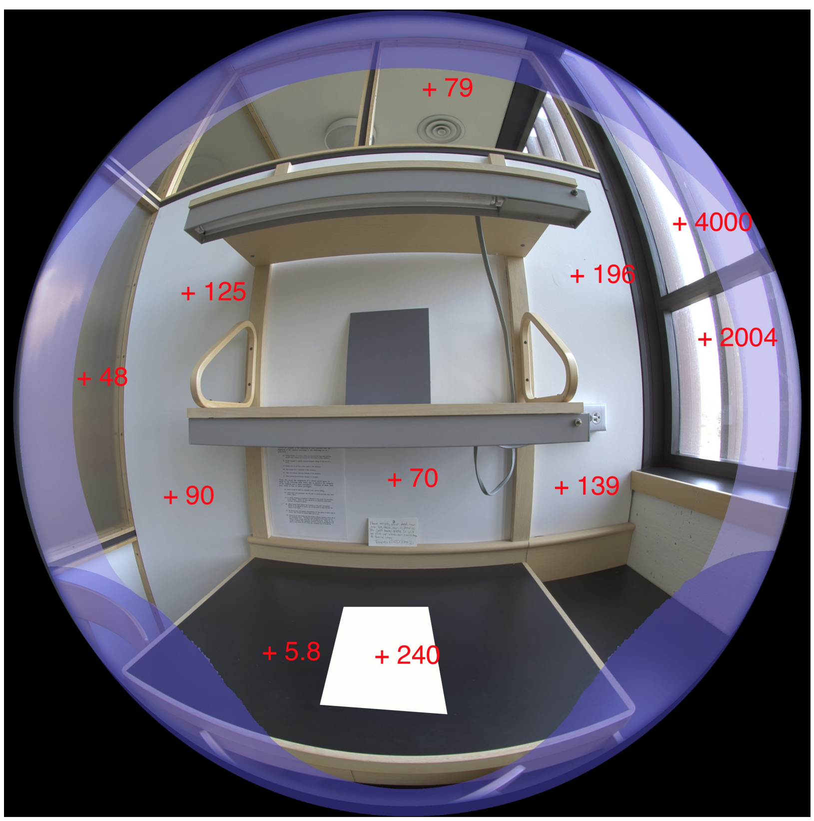


Fig. 4.10: View 2

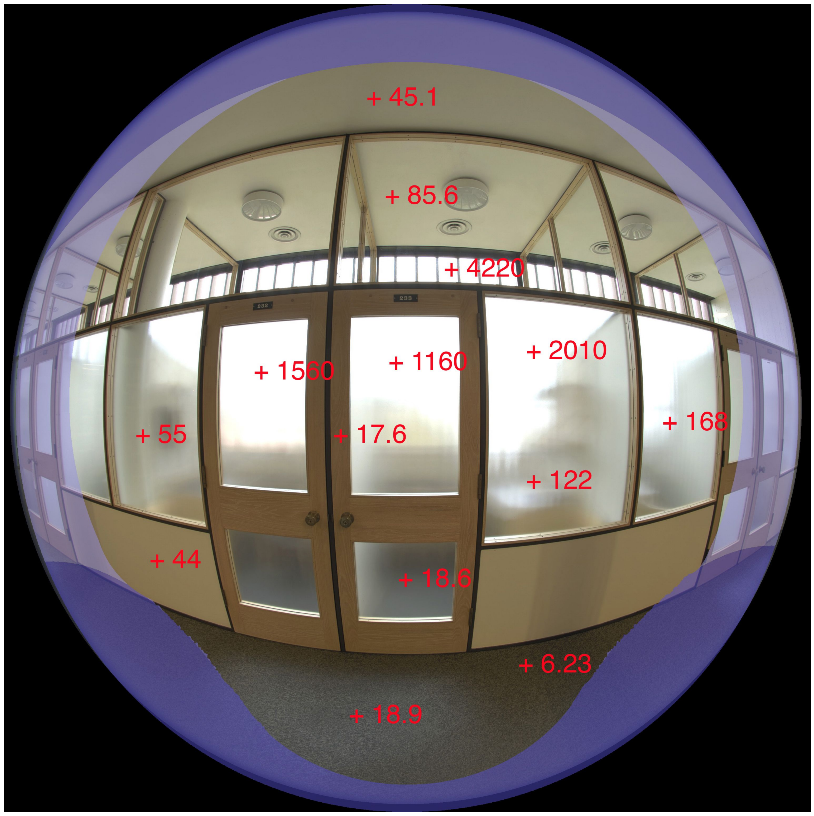


Fig. 4.11: View 3

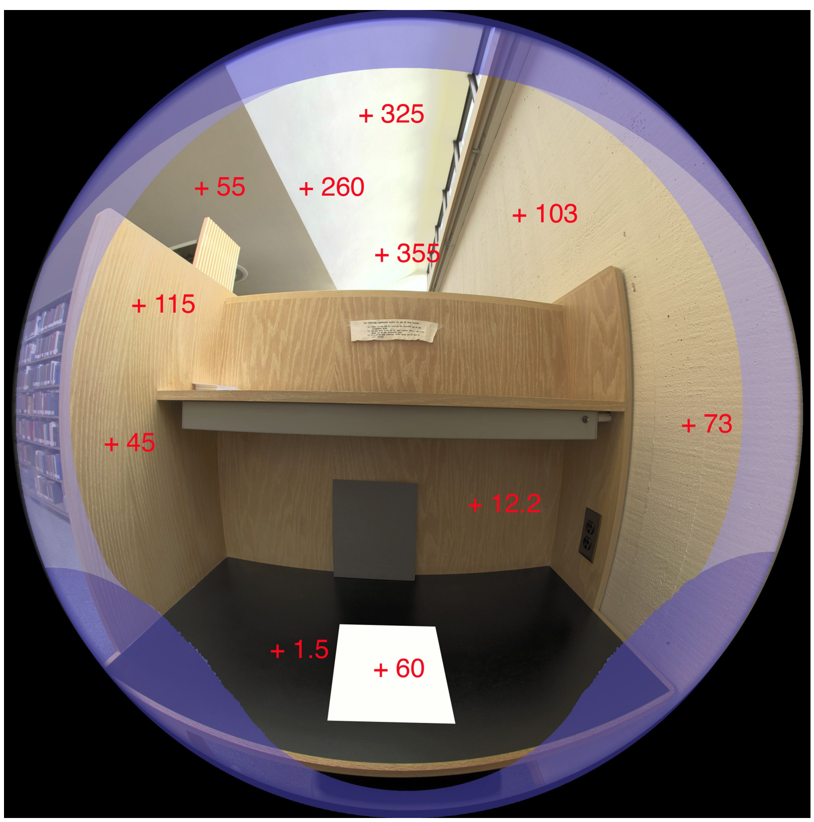


Fig. 4.12: View 4

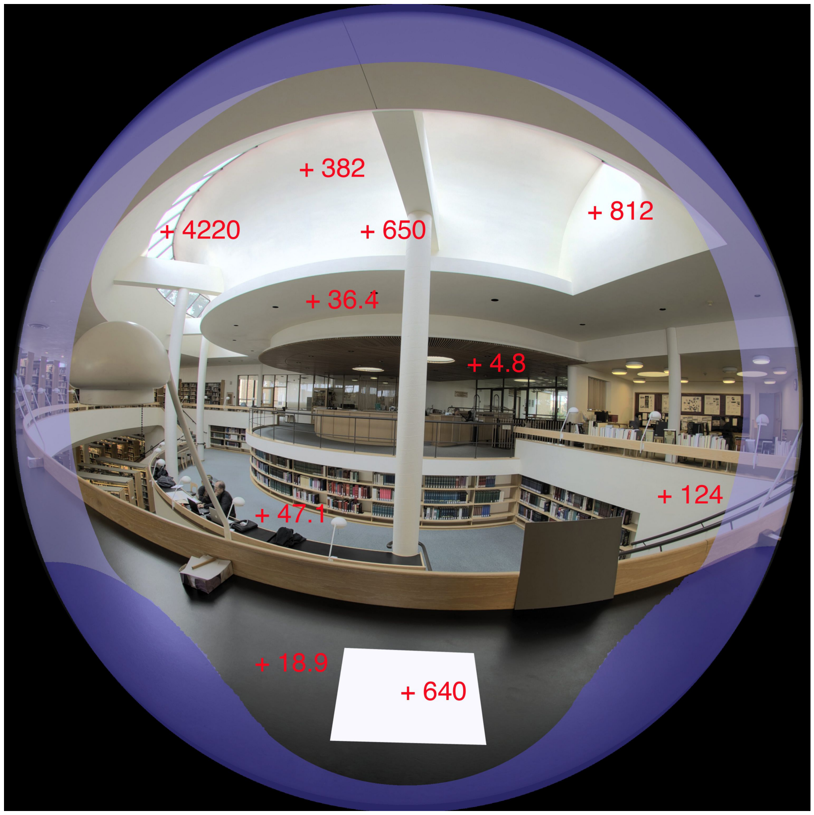


Fig. 4.13: View 5

Fig. 4.14: View 6

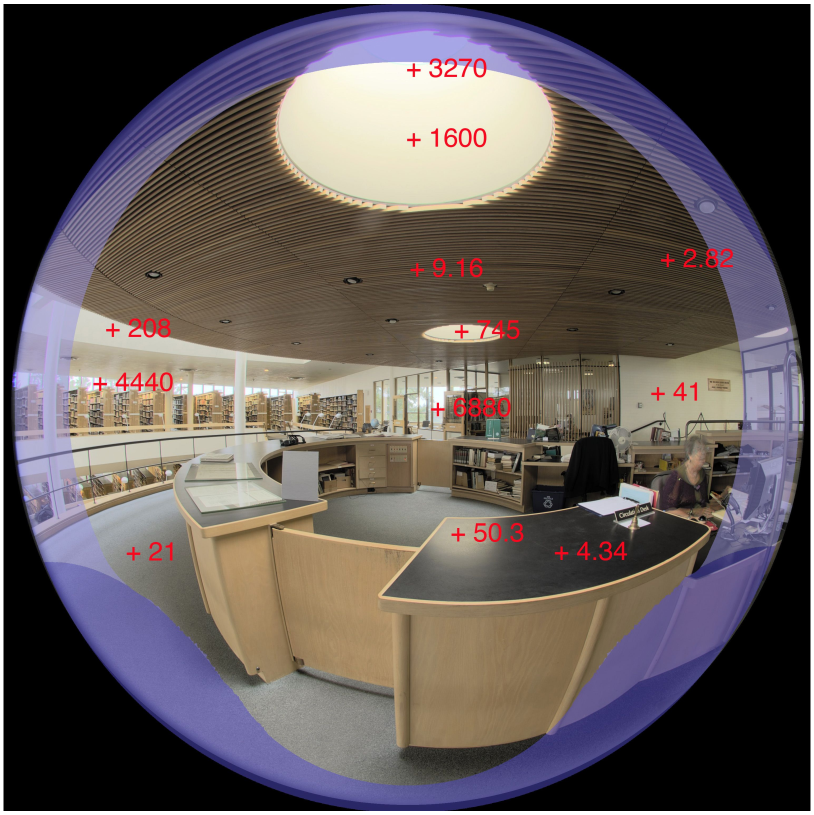


Fig. 4.15: View 7

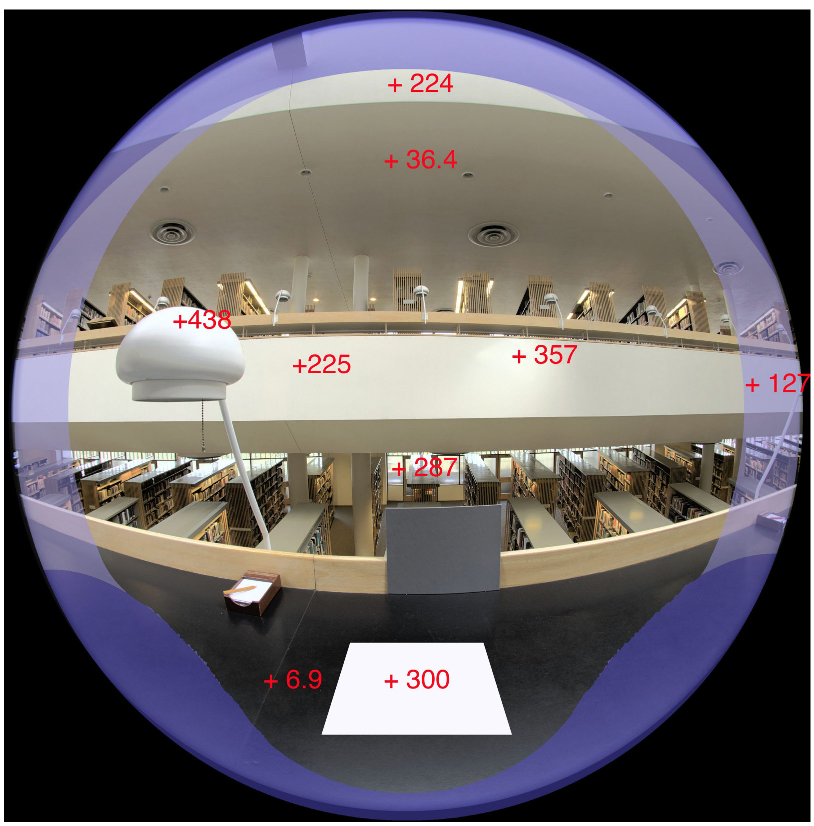


Fig. 4.16: View 8

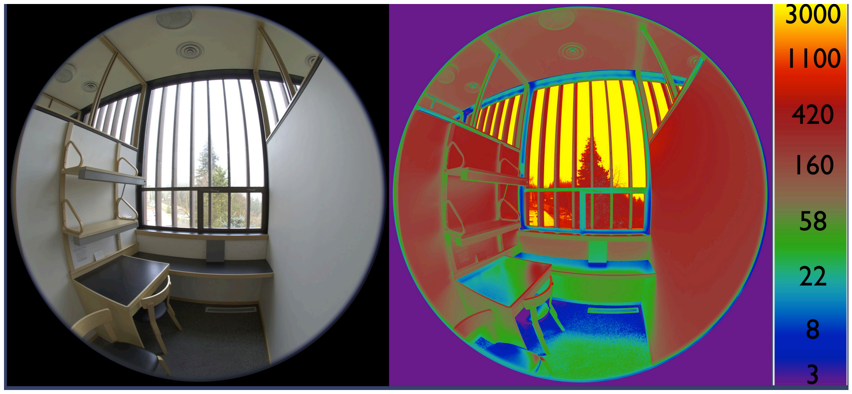


Fig. 4.17: The false color luminance map of View 1

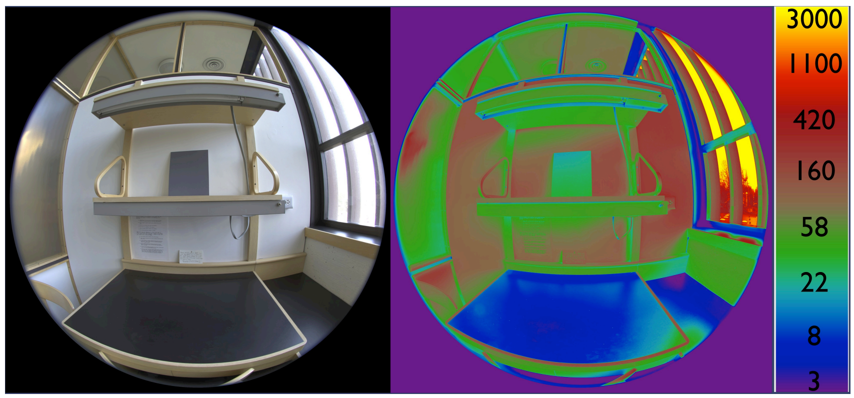


Fig. 4.18: The false color luminance map of View 2

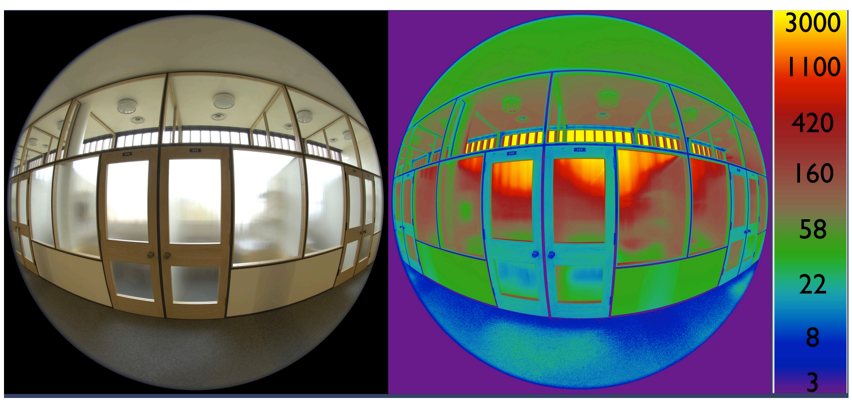


Fig. 4.19: The false color luminance map of View 3

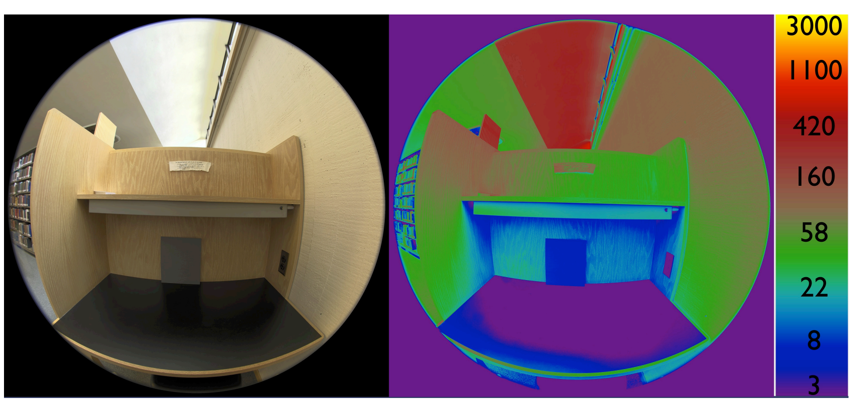


Fig. 4.20: The false color luminance map of View 4

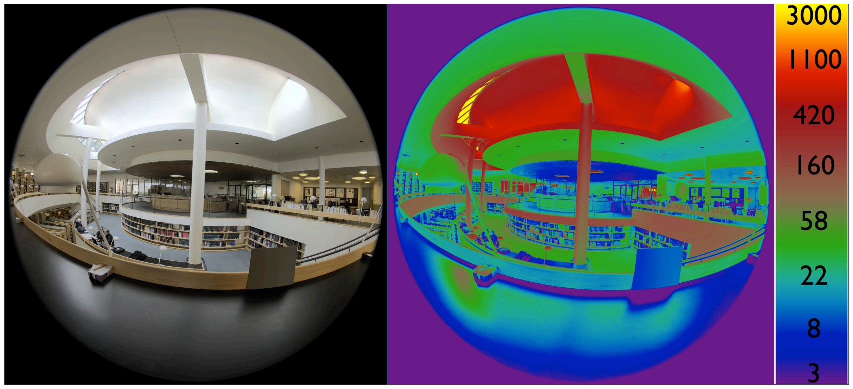


Fig. 4.21: The false color luminance map of View 5

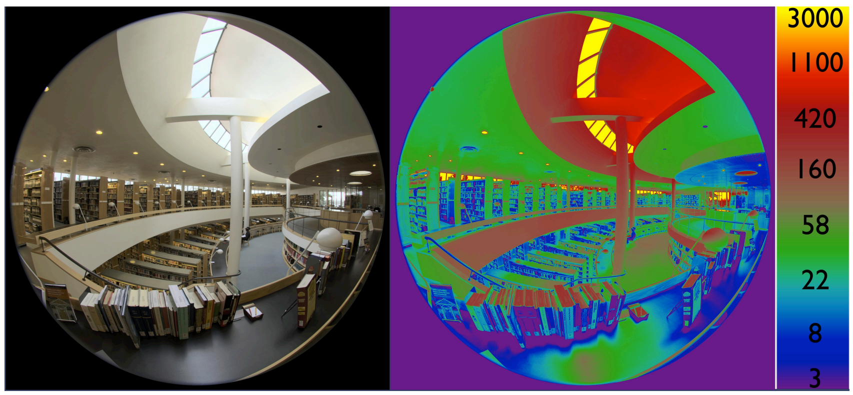


Fig. 4.22: The false color luminance map of View 6

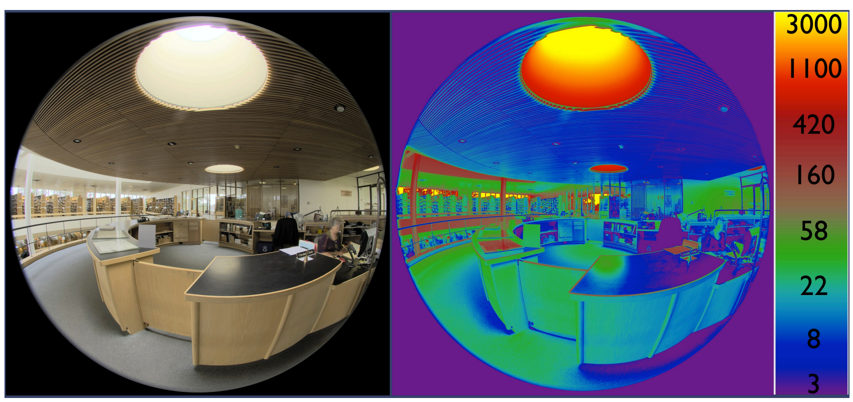


Fig. 4.23: The false color luminance map of View 7

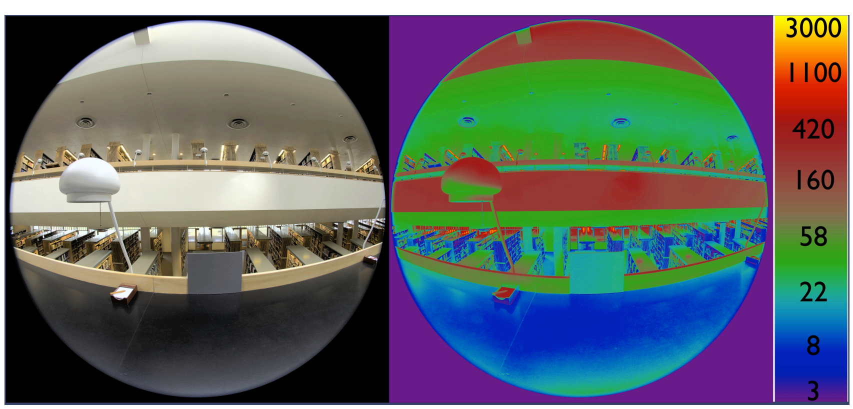


Fig. 4.24: The false color luminance map of View 8

4.4.6. Visual Comfort Assessment Using Glare Indices

As the third method of glare evaluation, the HDR images were processed with Evalglare to compute three different glare indices: DGP, DGI and UGR. As discussed earlier, in order to compute glare metrics, Evalglare requires a criterion to determine what regions in the image constitute a potential glare source. Two different criteria were used to identify the potential sources of glare: 1- any pixels with luminance of 2000 cd/m2 or higher, and 2- any pixels whose luminance exceed 7 times the average scene luminance. The latter is the criterion used by Radiance Findglare tool. Figures 4.25 and 4.26 show Evalglare check files in which the colored areas represent the potential sources of glare.

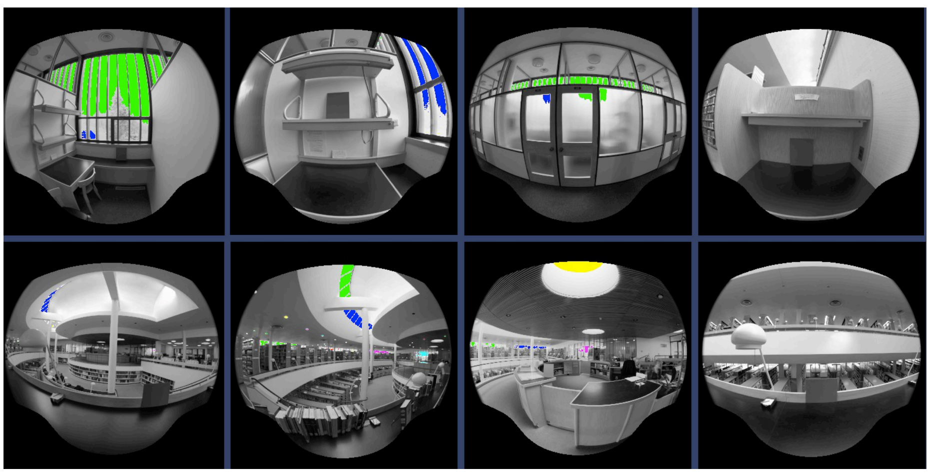


Fig. 4.25: Evalglare check files show pixels that exceed 2000 cd/m2 as colored areas.

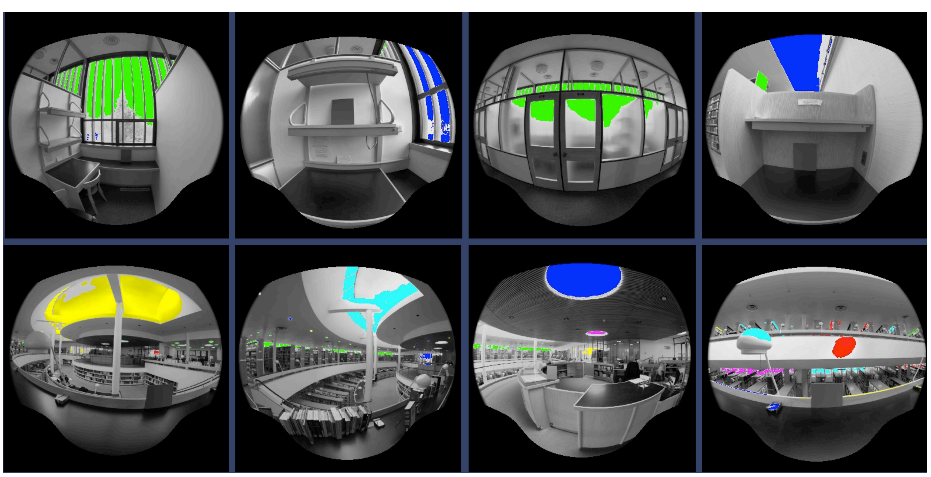


Fig. 4.26: Evalglare check files highlight pixels that are 7 times (or more) brighter than the scene average luminance.

Tables 4.3 and 4.4 show glare indices calculated for the images based on the 1st and 2nd criteria respectively. The glare metrics are interpreted according to table 4.5. It can be observed in tables 4.3 and 4.4 that with UGR method glare sensation is anticipated in most of the scenes, while DGP detects no glare at any of the views. DGI predicts moderate levels of glare in a few scenes. Between the two tables, however, the scene average based threshold resulted in higher glare index values compared to the absolute luminance threshold.

Table 4.3: Glare indices calculated for potential sources of glare identified through the absolute threshold of 2000 cd/m2

Location	DGP_{2000}		DGI_{2000}		UGR_{2000}	
	Value	Glare Sensation	Value	Glare Sensation	Value	Glare Sensation
View 1	0.30	Imperceptible	21.30	Perceptible	28.13	Intolerable
View 2	0.20	Imperceptible	13.57	Imperceptible	18.71	Perceptible
View 3	0.21	Imperceptible	16.01	Imperceptible	19.81	Perceptible
View 4	0.05	Imperceptible	inf	Imperceptible	inf	Imperceptible
View 5	0.16	Imperceptible	7.45	Imperceptible	9.79	Imperceptible
View 6	0.22	Imperceptible	19.26	Perceptible	21.38	Perceptible
View 7	0.21	Imperceptible	16.88	Imperceptible	19.05	Perceptible
View 8	0.08	Imperceptible	inf	Imperceptible	inf	Imperceptible

Table 4.4: Glare indices calculated for potential sources of glare identified through the scene average based threshold

Location	DGP_{7x}		DGI_{7x}		UGR_{7x}	
	Value	Glare Sensation	Value	Glare Sensation	Value	Glare Sensation
View 1	0.30	Imperceptible	21.06	Perceptible	27.94	Disturbing
View 2	0.21	Imperceptible	15.00	Imperceptible	20.25	Perceptible
View 3	0.23	Imperceptible	19.43	Perceptible	24.49	Disturbing
View 4	0.05	Imperceptible	3.00	Imperceptible	4.77	Imperceptible
View 5	0.17	Imperceptible	11.84	Imperceptible	14.84	Perceptible
View 6	0.21	Imperceptible	18.32	Perceptible	20.30	Perceptible
View 7	0.21	Imperceptible	17.94	Imperceptible	20.20	Perceptible
View 8	0.09	Imperceptible	11.77	Imperceptible	12.25	Imperceptible

Table 4.5: Glare index interpretation guide

Criterion	**DGP**	**DGI**	**UGR**
Intolerable Glare	> 0.45	> 31	> 28
Disturbing Glare	0.4 - 0.45	24-31	22-28
Perceptible Glare	0.35 - 0.45	18-24	13-22
Imperceptible Glare	< 0.35	< 18	< 13

4.4.7. Comparison of Results

Visual comfort in Mt. Angel Abby library was assessed through three different methods: IESNA recommended ratios, Pixel percent method, and glare indices. Table 4.6 shows the probability of glare sensation inside the building predicated by each of these methods. It displays a wide disparity between the glare evaluation metrics, in that one method predicts no glare in any of the scenes while another method assumes visual discomfort in all of the studied locations.

Table 4.6: Glare sensation probability predicted by discussed methods

	DGP_{2000}	DGI_{2000}	UGR_{2000}	DGP_{7x}	DGI_{7x}	UGR_{7x}	IESNA Ratios	Pixel Percent
View 1	Comfort	Glare	Glare	Comfort	Glare	Glare	Glare	Glare
View 2	Comfort	Comfort	Glare	Comfort	Comfort	Glare	Glare	Comfort
View 3	Comfort	Comfort	Glare	Comfort	Glare	Glare	Glare	Comfort
View 4	Comfort	Comfort	Comfort	Comfort	Comfort	Comfort	Glare	Comfort
View 5	Comfort	Comfort	Comfort	Comfort	Comfort	Glare	Glare	Comfort
View 6	Comfort	Glare	Glare	Comfort	Glare	Glare	Glare	Comfort
View 7	Comfort	Comfort	Glare	Comfort	Comfort	Glare	Glare	Comfort
View 8	Comfort	Comfort	Comfort	Comfort	Comfort	Comfort	Glare	Comfort

Since the author did not experience any discomfort glare while acquiring the HDR images, it can be concluded that DGP is a reliable metric for visual comfort assessment of a daylit space. The study confirmed that UGR overestimate glare from daylight, and DGI occasionally produces erroneous results. Another interesting outcome was that the pixel percent method performed closely to the DGP method. This is significant considering its simplicity compared to other methods. Accordingly, it can be used in a rule of thumb fashion for quick glare assessments.

4.5. DISCUSSION AND CONCLUSION

This chapter discussed daylight performance metrics with an in-depth look at the current visual comfort assessment methods. Visual comfort is a key aspect of a successful

daylighting design. It has been suggested that it is equally or more important than the daylight sufficiency for task performance. Unlike the daylight availability metrics that are widely used and have been firmly established, glare assessment methods are still under development. Therefore it was essential for the author to decide which method to use for glare evaluation of the subdivided windows in the next two chapters. After examining a number of glare evaluation techniques, it was decided that DGP is the most reliable method to predict glare sensation in a daylit space.

CHAPTER 5
Design Options for Subdivided Windows

This chapter examines a number of design options for subdivided windows. As discussed in chapter 3, subdivided windows in which occupants control the lower shades reveal better daylight condition compared to unsubdivided windows. It was also suggested that an automatic shading device on the upper part of the subdivided windows might further improve their daylight performance. In this chapter, various dynamic shading systems on subdivided windows are evaluated using Radiance simulation program.

5.1. DYNAMIC SHADING DESIGN

Currently a variety of automatic shading devices are available. They include motorized roller shades, switchable glazing systems and dynamic louver systems. In selecting the design options for evaluation, the goal was to consider dynamic shading devices that do not block but redirect daylight when activated. Accordingly, this research focuses on louver systems as they allow reflected and diffuse light into the space, while controlling direct sunlight. To create a dynamic louver system, one option is to mobilize the slats. The other option is to keep them fixed but change their light transmission properties. The latter could be achieved by the use of switchable materials such as electrochromic glass and liquid crystal glass. A solid louver system was included in Radiance simulations as a control system. Therefore the four alternatives in this study consist of subdivided windows with occupant-controlled venetian blinds on the lower part of the window and the following shading devices on the upper part:

1- Liquid Crystal glass louvers

2- Electrochromic glass louvers

3- Motorized opaque louvers

4- Fixed opaque louvers

5.1.1. Switchable Glass Louvers

Switchable glass is referred to materials that change their optical properties with a change in electric current. Electrochromic glass and Liquid Crystal glass are two examples of a switchable glazing system. Liquid Crystal (LC) technology is usually used in privacy glass systems. An LC device is compromised of a thin layer of liquid crystals sandwiched between two transparent electrical conductors laminated between two layers of glass. In their non-energized state liquid crystals are unaligned and scatter transmitted light. Therefore the glass appears translucent. When power is applied, the liquid crystals are arranged in a specific direction permitting the parallel admission of light, hence a transparent view through the glass (Figure 5.1). Liquid Crystal devices are mainly used for interior applications ("Windows for High Performance," n.d.).

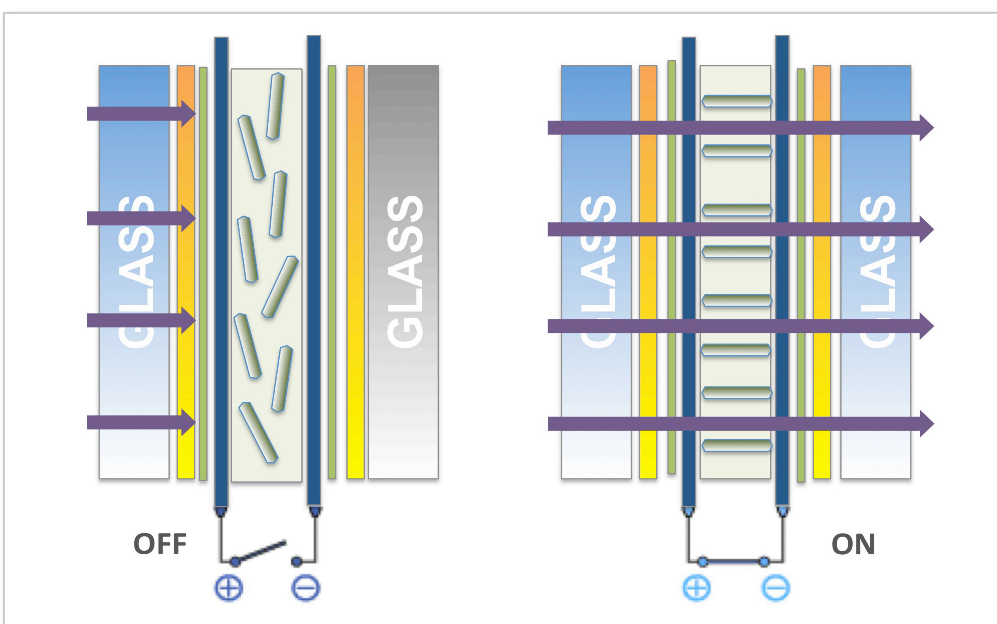


Fig. 5.1: Liquid crystal glass technology

Electrochromic (EC) glass is used to control solar heat gain and glare in exterior windows. An EC glass consists of several layers of materials including a transparent conductor, an electrochromic coating, an ion storage layer, an ionic conductor, and a counter electrode all laminated between two panes of glass. When a voltage is applied between the transparent electrical conductors, various coloration ions move from ion storage film into the electrochromic film. The effect is that the glazing switches from clear to blue-gray tinted state with no change in transparency. Table 5.1 compares general properties of LC glass with EC glass (Baetens et al., 2010, "Windows for High Performance," n.d.). Figure 5.2 shows light transmission through each glass type. The EC glass at its tinted state reduces the amount of transmitted light without affecting its direction, whereas the LC glass in hazed state diffuses light without significantly changing its transmittance.

Table 5.1: General properties of liquid crystal and electrochromic glass

Switchable Glass	Visible Transmittance Range	SHGC	Electrical Demand	Modulation	Minimum Thickness
Electrochromic Glass	2 % – 70%	0.10 – 0.50	0 –10 volts DC	Can be modulated to intermediate states between clear and fully colored.	9 mm
Liquid Crystal Glass	50% – 80%	0.55 – 0.69	24 –100 volts AC about 0.5 W/sf	Only two states: clear and diffusing	9 mm

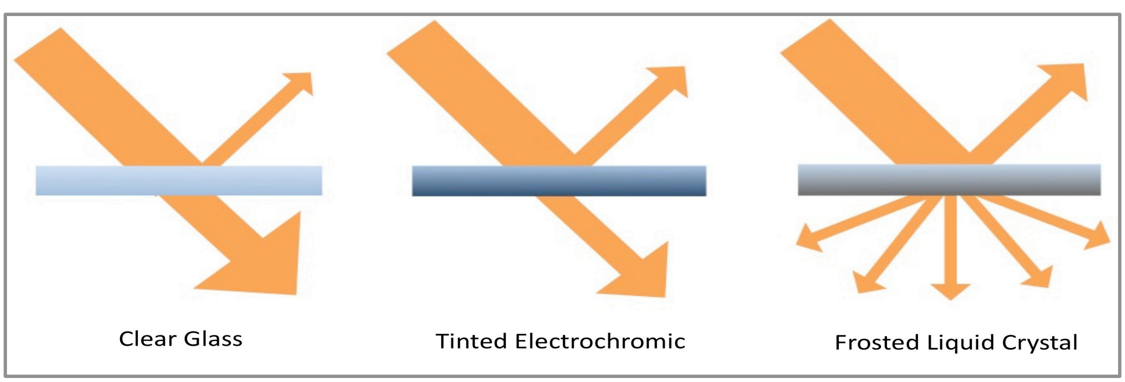


Fig. 5.2: Light Transmission through EC and LC glass

Traditionally switchable glass is installed vertically within the glazing system. However in this study two of the design options propose the use of switchable glass in the form of horizontal louvers. With this configuration the tinted or hazed louvers will control the direct sunlight falling on the work surface while admitting the diffuse daylight. Whereas in vertical installation, the switchable glass reduces general daylight admission when tinted or frosted. Additionally, switchable glass louvers seem visually more appealing than the switchable windows. Commercially available Elctrochromic glass has a blue tint and affects the color of transmitted light when activated. However, it will look less disturbing when it is seen as horizontal blue bands against the clear window (Figure 5.3). The same fact is true as to the Liquid Crystal glass. Turning the window pane into translucent glass impairs the view out, but using LC glass in louvers will preserve some of the view and is aesthetically more pleasing (Figure 5.3).

Table 5.2 shows the optical properties of the LC and EC glass louvers as well as the opaque louvers modeled in this study. Please note the higher reflectivity of the LC glass in its translucent state and the lower transmittance of the EC glass in its tinted state.

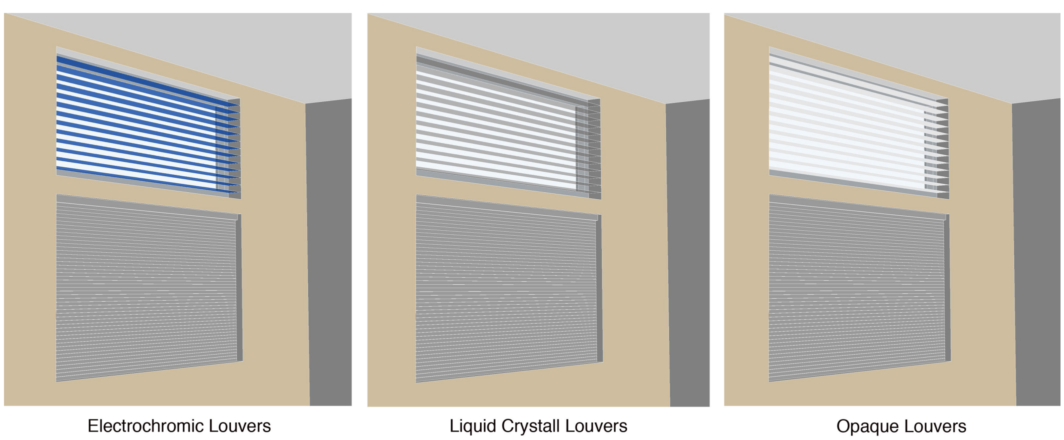


Fig. 5.3: Subdivided windows with venetian blinds on the lower part and EC, LC, and opaque louvers on the upper part respectively from left.

An ideal switchable material would be one with a high reflectance and low transmittance in non-clear state. But such material does not exist yet.

Table 5.2: The optical properties of the LC, EC and opaque louvers modeled in Radiance. Source: Sage Electrochromic & SmartGlass International, Ltd.

Optical Property	LC Glass		EC Glass		Opaque Louver
	Clear	Translucent	Clear	Tinted	
Reflectance	14%	18%	17%	6%	70%
Visible Transmittance	75%	67%	70%	40%	0
Clarity	67%	4%	-	-	0

5.1.2. Motorized Louver System

Motorized louvers or blinds are usually equipped with a motor which drops, retracts and controls the tilt of the blind slats. The motorized louver system studied here consists of automatically controlled horizontal slats of white color. The louvers move top-down, but do not change their tilt. Annual daylight performance of this system along with the other three alternatives were studied using Radiance simulation. The following section discusses the simulation process.

5.2. SIMULATING DESIGN OPTIONS WITH RADIANCE

Radiance is a backward ray-tracer, i.e. it traces the light rays from the sensor point or image pixel back to the light source (Ward & Shakespeare, 1998). In daylighting simulations, Radiance sends out a number of rays from the interest point and follows a definite number of reflections until the rays pass through the window and hit the sky dome. The user defines the number of the outgoing rays (ambient division) as well as the number of reflections (ambient bounces) to be followed based on the complexity of the model. When modeling a simple fenestration such as a window with a glass, low parameters like ab=2 and ad=512 will be adequate. But with Complex Fenestration Systems (CFS) designed to redirect daylight, the parameters have to be set really high in

order to make sure the rays find their way out of the window and hit the sky dome. This will tremendously increase the simulation time. Especially, if one intends to perform an annual hourly daylighting simulation.

The annual daylight analysis with Radiance has recently been made possible by two concepts of daylight coefficient and Perez sky model. In daylight coefficient concept, the sky dome is divided into 145 patches and the contribution of each sky patch to the illumination of a point in the space is calculated as a coefficient (Tregenza 1983) (Figure 5.4). Perez sky model takes the TMY weather data and creates hourly sky models that represent luminance distribution of the sky at each hour (Perez, Seals, & Michalsky, 1993). For an annual calculation, the illuminance at the point is calculated for each time step by multiplying the luminance of the sky divisions by their respective daylight coefficient then summing the 145 resultant values (Bourgeois et al., 2008).

5.2.1. The 3-phase and 5-phase Method for Modeling Complex Fenestration with Radiance

There are a number of Radiance-based programs (e.g. DAYSIM) that use daylight coefficient method to perform annual hourly daylight calculations. While they can

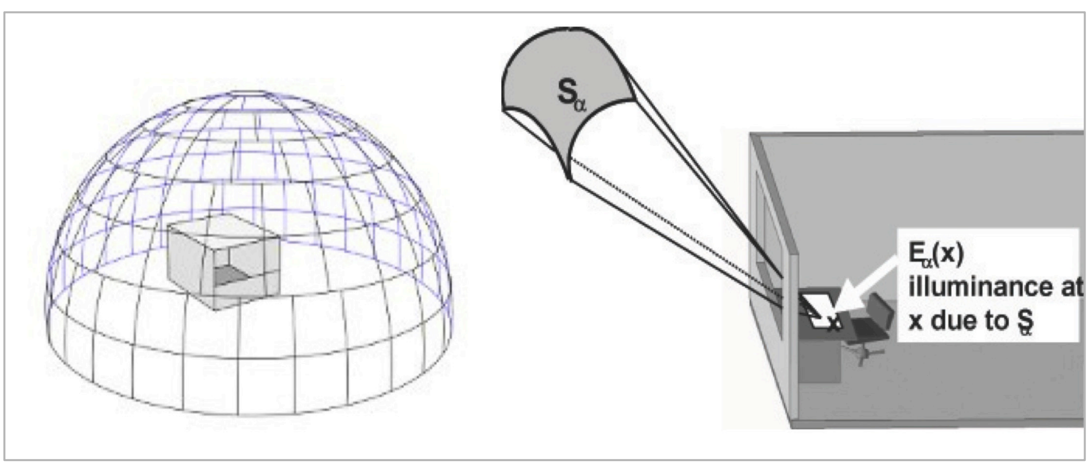


Fig. 5.4: Daylight coefficient concept. Source: Reinhart, 2009 and Radiance-online.org.

produce reliable results with non-complex conventional shades, they are not able to simulate complex fenestrations or specularly reflecting daylighting systems (McNeil & Lee, 2013). The light transmission pattern through such systems is specifically monitored either in laboratory using a Goniophotometer or virtually through raytracing tools. The resultant data is stored in a matrix form and is known as BSDF data. Bidirectional Scattering Distribution Functions (BSDF), proposed by Klems (1994a, 1994b), determine the direction of the reflected and transmitted light for all incident directions defined by the hemisphere viewed by the window (Figure 5.5).

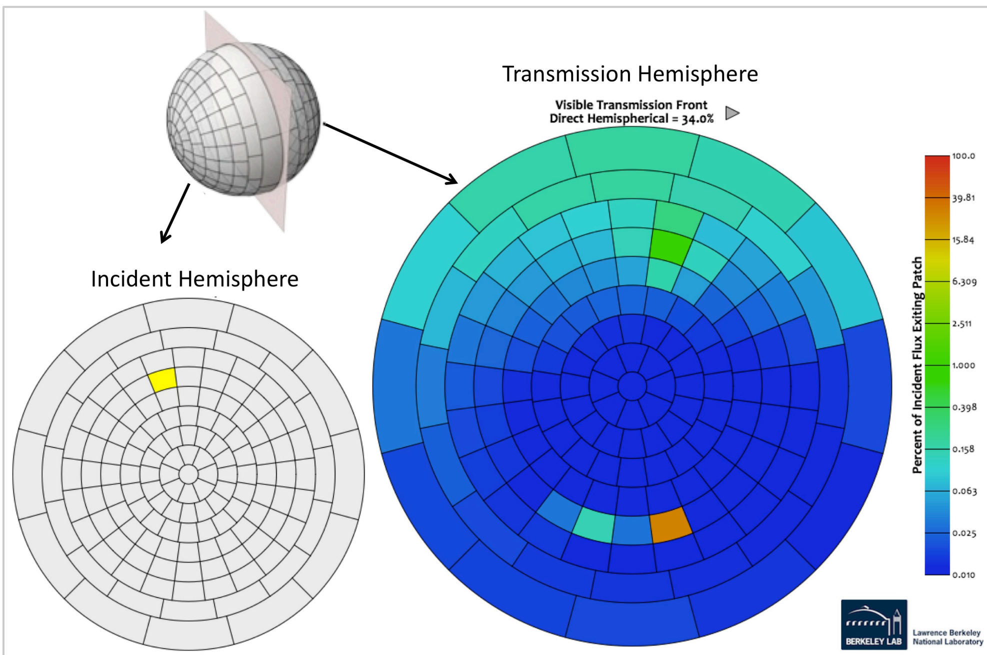


Fig. 5.5: Bidirectional Scattering Distribution Functions relate energy incident on a Window and energy leaving a window in Klems directional bins. Image produced by LNBL's BSDF Viewer software (McNeil, 2013).

In 2010, new tools were added to Radiance that facilitated the use of Klems' BSDF data in annual daylight simulations (Ward, Mistrick, Lee, McNeil, & Jonsson, 2011). With the combination of these tools, Ward developed a three-phase method for annual simulation of complex fenestration with Radiance (McNeil, 2013a). In three-phase method, flux transfer from the sky to the point in the space is broken into three phases:

1. Sky to exterior of fenestration
2. Transmission through fenestration
3. Interior of fenestration into the simulated space

Each phase of light transport is simulated independently and stored in a matrix form. The resultant illumination is obtained using matrix multiplication (McNeil & Lee, 2013). This approach enables quick computation of many fenestration types, locations and facade orientations by simply substituting the transmission matrix or sky data. More important, this approach helps simulate the performance of complex fenestration systems that can not normally be simulated in daylight analysis programs (McNeil & Lee, 2013). Recently, the three-phase method has been extended to a five-phase method, as it did not model direct sun distribution accurately (McNeil, 2013b). The basic approach of the 5-phase method is as follows:

1. Perform a three-phase simulation
2. Subtract the direct solar contribution (leaving the inter-reflected solar component)
3. Add direct solar contribution that is more accurately simulated

Fig 5.6 illustrates the terms of the 5-phase method. The four design options in this study were evaluated both with three-phase and five-phase method, as the five-phase method was published after the completion of the three-phase method simulations. It provided an opportunity to compare the results from each method. In case of dynamic shading devices, an annual hourly simulation was performed for each state of the shades. Then the resultant data was filtered using the control algorithms and occupancy schedules discussed in section 5.3. A complete description of the simulation steps and Radiance scripts are included in Appendices C and D.

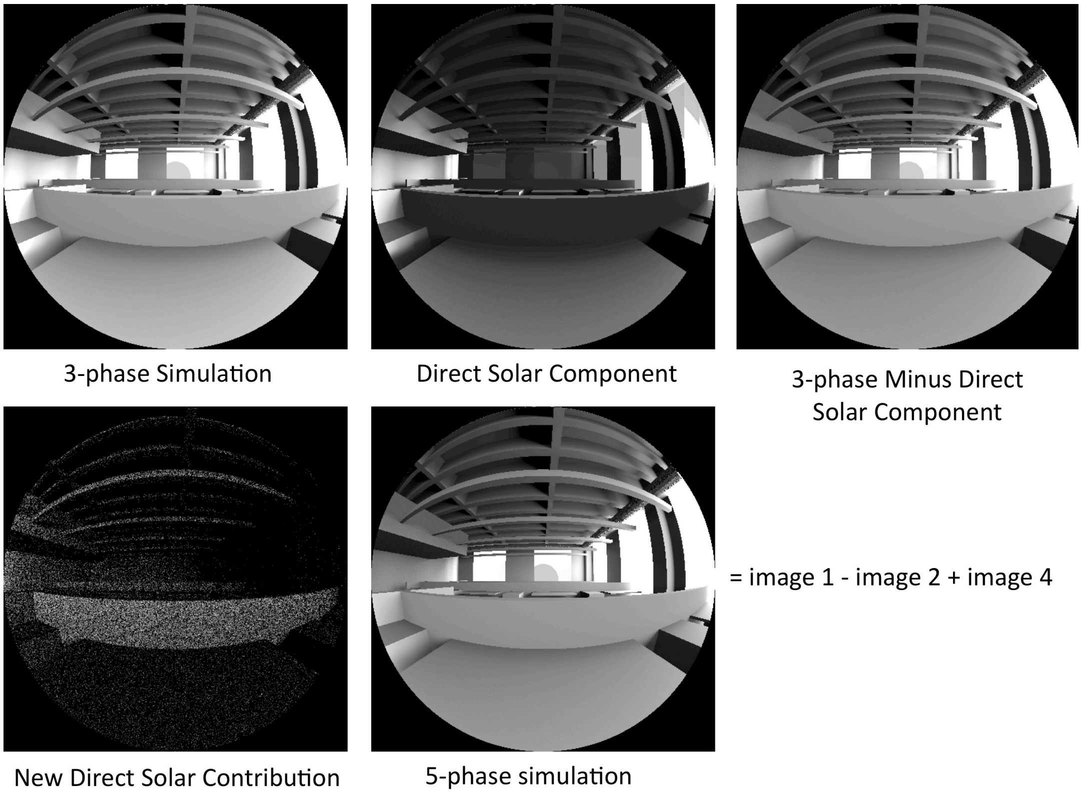


Fig. 5.6: The 5-phase method simulation terms

5.2.2. Model Description

A virtual workspace was modeled in Radiance to assess the performance of the shading devices. The test room measures 6 by 8 by 2.7 meters with two south facing windows (Figure 5.7). Table 5.3 shows the room and window material properties. The upper louvers were designed 10 centimeters deep and 5 centimeters apart. The LC

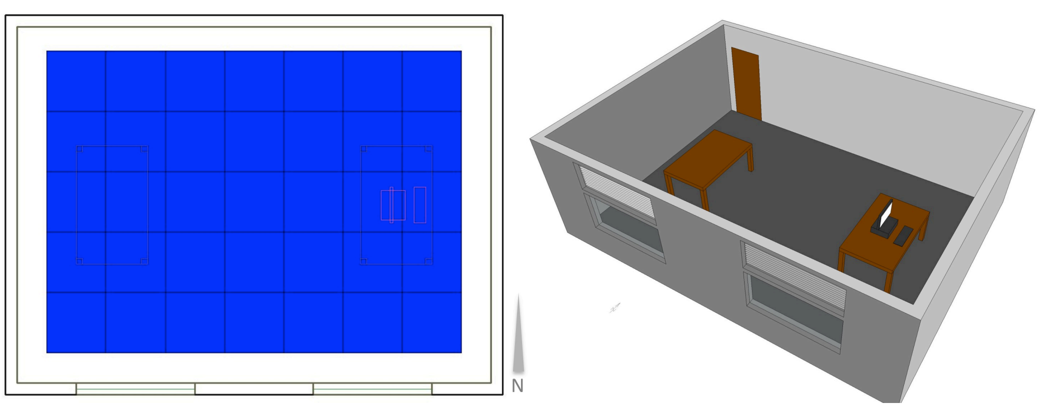


Fig. 5.7: The room model (right) and the grid of 48 sensors (left).

Table 5.3: The optical properties of the LC, EC and opaque louvers

Material	Reflectance or Transmittance
Window wall and Side walls	50%
Back wall	75%
Ceiling	80%
Floor	30%
Window glazing	VT: 72%

louvers were modeled as “trans” material type in Radiance to maintain their light diffusing properties. Each shading device was modeled in two states of fully open/clear and fully closed/darkened. 48 sensor points were defined at work level inside the room.

The systems’ annual daylight performances were evaluated in five different cities: Seattle, Milwaukee, San Francisco, Dallas, and Phoenix. Each city represents a different zone in the solar energy distribution map (Figure 5.8). Since the upper and lower shading devices were on different control algorithms, the 4 subdivided windows resulted in 12 different scenarios to be modeled in Radiance (Table 5.4).

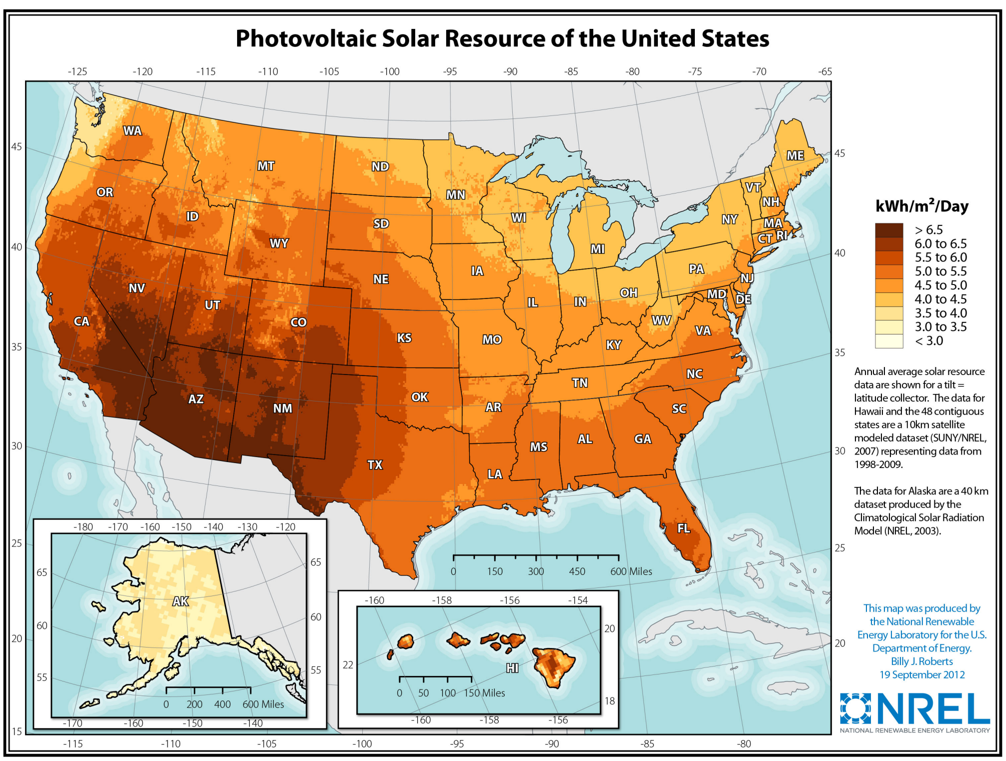


Fig. 5.8: Solar energy distribution map. Source: National Renewable Energy Lab website.

A full year simulation was performed for each scenario and each city. This resulted in 60 sets of annual illuminance data. Then in a spread sheet the illuminance data were filtered and consolidated based on the control algorithms discussed in the following section. Finally, the annual daylight metrics were calculated from the processed illuminance data.

Table 5.4: The 12 scenarios of subdivided windows modeled in Radiance

Scenario	Upper Shading System	Upper Louvers State	Venetian Blind State
1	Liquid Crystal louvers	Translucent	Closed
2	Liquid Crystal louvers	Translucent	Open
3	Liquid Crystal louvers	Clear	Closed
4	Liquid Crystal louvers	Clear	Open
5	Electrochromic louvers	Tinted	Closed
6	Electrochromic louvers	Tinted	Open
7	Electrochromic louvers	Clear	Closed
8	Electrochromic louvers	Clear	Open
9	Motorized louvers	Retracted	Closed
10	Motorized louvers	Retracted	Open
11	Motorized louvers / Fixed louvers	Lowered	Closed
12	Motorized louvers / Fixed louvers	Lowered	Open

5.3. CONTROL ALGORITHM FOR DYNAMIC SHADING

As discussed earlier, the shade control algorithm was defined separately for occupant-controlled and automatically controlled shading devices. The control algorithm for occupant-controlled venetian blinds takes transmitted vertical irradiance as input, while the control algorithm for automatic shading devices takes sky condition as input. This is because the former has a predictive nature, while the latter is the actual setting of the automatic shading device.

5.3.1. Control Algorithm for Venetian Blinds

It is very difficult to predict when occupants adjust shading devices. A number of shade control behavior studies have tried to create a link between solar radiation data and

occupants' use of shades. These studies have resulted in a number of shade control behavioral models summarized in table 5.5. It is important to note that these models are based on two states of the shades and can not predict intermediate shade positions and slat angles. Accordingly, the venetian blinds in this study were modeled in two states, fully retracted and fully lowered with slats at 80 degrees from the window normal.

Table 5.5:Existing Shade Control behavioral Models (Konis, 2011)

Model	Criteria for lowering	Criteria for raising
Reinhart, 2002	If irrad > 50 W/m^2	Shades raised on arrival on following workday
Lee and Selkowitz, 1995	If irrad > 95 W/m^2	If irrad < 95 W/m^2, shades raised after one hour
LEED, 2012	If direct sun incident on workspace	If no direct sun incident on workspace, shade raised
Inkarojrit, 2005	If irrad = 13 W/m^2 50% proboblity	NA, shades are not raised

Reinhart's (2002) model was selected to predict occupant shade control behavior. The model assumes that occupants deploy the venetian blinds when the transmitted solar radiation exceeds 50 W/m2. Once lowered, the shades stay down for the rest of the day and are opened in the next morning. Although the shade raising criteria may not be true in most buildings, it seemed appropriate for this study. Because chapter 3 showed that subdivided windows will increase occupants' chance of opening the shades. The hourly transmitted vertical irradiance was calculated from the date, time, latitude, direct normal and diffuse horizontal irradiance data at each time step (Equations 5.1 to 5.5).

5.3.2. Control Algorithm for Automatic Shading Devices

The control algorithm for automatic shading devices is based on the presence of direct sunlight. Table 5.6 shows the criteria for determining the sky condition from the direct normal and diffuse irradiance data (Fernandes, Lee, & Ward, 2013). This study assumed that the automatic shading devices would be activated when direct normal

Equations 5.1 to 5.5: Calculation of the transmitted vertical irradiance through the south facing windows

Transmitted Vertical Irradiance = I_south,vertical x *SHGC*

I_south,vertical = I_global,diffuse / 2 + I_direct,normal x *Cos(incident) + GroundReflectance* x *I_global,horizontal / 2*

I_global,horizontal = I_global,diffuse + I_direct,normal x *Cos(zenith)*

Cos(zenith) = Cos(latitude) x *Cos(declination)* x *Cos(hourAngle) + Sin(latitude)* x *Sin(declination)*

For equator facing vertical facades, the incident angle is given as:
Cos(incident) = -Sin(declination) x *Cos(latitude) + Cos(declination)* x *Sin(latitude)* x *Cos(hourAngle)*

where:

"declination" is the declination angle of the earth given in angles:
declination = 23.45 x *Sin(360 (284 + nDay) / 365)*

"latitude" is the latitude of the wall, north is positive.

"nDay" is the day number of the year (jan 1 equals 1, dec 31 equals 365).

"hourAngle" is the hour angle of solar time (solar time is zero at solar noon, negative in the morning and positive in the afternoon. One hour of solar time is 15 degrees; e.g. The hourAngle of 10:15 am solartime is -26.25° [-15 * 1.75]).

irradiance is equal or grater than 50% of diffuse horizontal irradiance. Based on table 5.6 values, this represents a sky with 70 percent cloud cover. In other words, the automatic shading devices are activated when 0 to 70 percent of sky is covered with clouds. The shading devices remain in their sun-blocking state for at least one hour, so they do not annoy occupants by constant alternation in cloudy days. Figure 5.9 summarizes the control algorithm of automatic louvers and venetian blinds.

Table 5.6: Predicting sky condition based on direct normal and diffuse horizontal irradiance (Fernandes, Lee, & Ward, 2013)

Sky type	**Condition**
Clear	Direct normal irradiance is more than 200% of diffuse horizontal irradiance
Intermediate	Direct normal is between 5% and 200% of diffuse horizontal irradiance
Overcast	Direct normal is less than 5% of diffuse horizontal irradiance

If I_transmitted > 50 W/m² ⇒ *Venetian blinds are closed.*
If I_direct normal > 0.5 x *I_diffuse horizontal* ⇒ *Upper shading is lowered/tinted/hazed.*

Fig 5.9: Summery of control algorithms

5.3.3. Occupancy Schedules

The illuminance data was also filtered based on the normal working hours (8 A.M to 5 P.M.). Therefore any illuminance values that occurred before 8 A.M. and after 5 P.M. were eliminated.

5.4. DAYLIGHT PERFORMANCE RESULTS

Radiance simulations revealed two sets of results: hourly illuminance data at the sensor points and rendered images of a viewpoint. The illuminance data was used to calculate dynamic daylight metrics. The rendered images were used for glare evaluation.

5.4.1. Useful Daylight Illuminance

To assess the performance of the proposed window designs in terms of daylight sufficiency, two metrics of Useful Daylight Illuminance (UDI) and Daylight Autonomy (DA) were calculated form the resultant hourly illuminance profiles. Useful Daylight Illuminance proposed by Nabil and Mardaljevic (2005) is based on the same concept, except that it includes a discomfort threshold as well.

UDI is originally defines as the percentage of the occupied hours of the year when the illuminance at the workplane is between 100 and 2000 lux. In this study however the minimum threshold is increased to 200 lux to comply with the minimum light level required for computer-based tasks. Table 5.7 and 5.8 show the average UDI in the room resulted from the 3-phase and 5-phase simulation of the shading systems respectively. Figures 5.10 and 5.11 are the graphical representation of above tables.

Table 5.7: Average UDI(200-2000) resulted from the 3-phase method simulations

	Opaque Louvers	Liquid Crystal Louvers	Electrochromic Louvers	Motorized Louvers
Dallas	47.24%	63.91%	21.56%	59.25%
Milwaukee	46.06%	58.72%	25.01%	60.69%
Phoenix	58.31%	70.98%	23.07%	61.44%
San Francisco	53.33%	65.78%	23.55%	59.84%
Seattle	44.48%	54.90%	24.77%	56.69%

Table 5.8: Average UDI(200-2000) resulted from the 5-phase method simulations

	Opaque Louvers	Liquid Crystal Louvers	Electrochromic Louvers	Motorized Louvers
Dallas	77.88%	81.04%	82.74%	83.97%
Milwaukee	68.18%	72.18%	72.99%	76.24%
Phoenix	85.75%	86.43%	87.78%	87.39%
San Francisco	77.89%	79.55%	80.93%	81.41%
Seattle	63.82%	67.45%	68.19%	71.42%

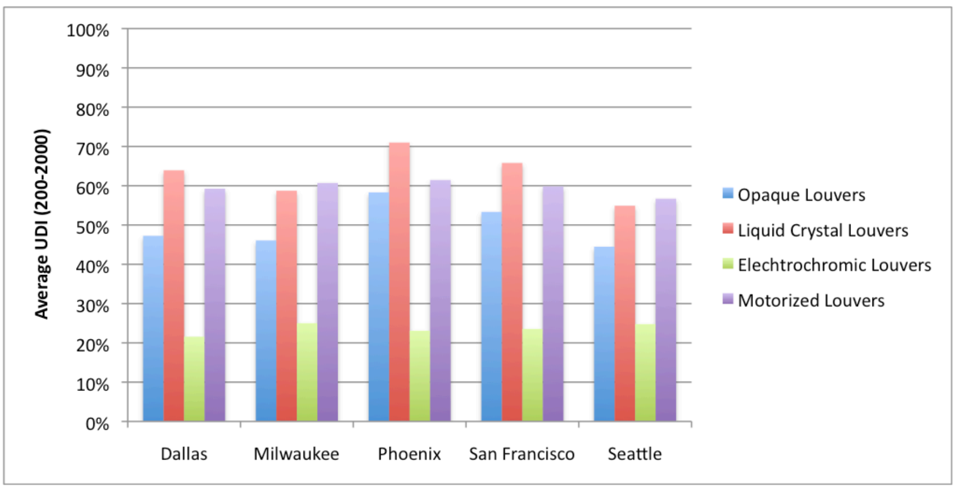


Fig. 5.10: Average UDI in the room obtained from the 3-phase method simulation

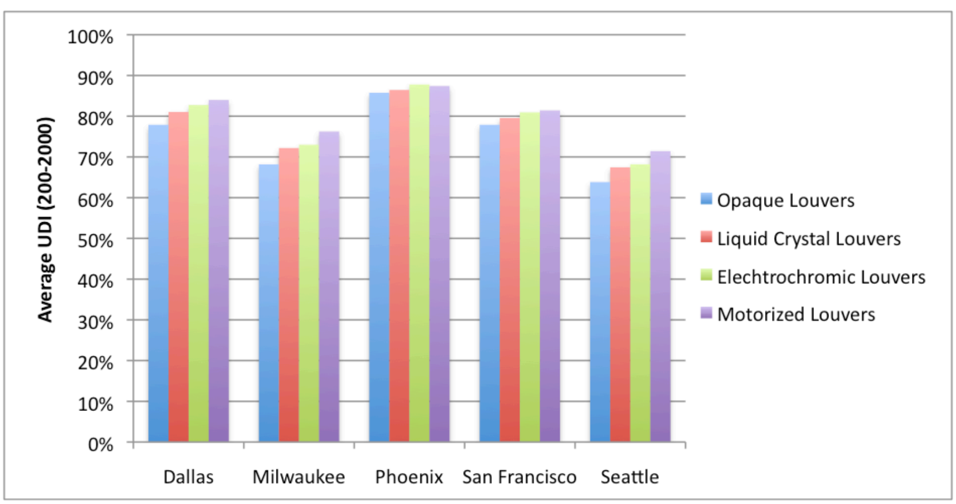


Fig. 5.11: Average UDI in the room obtained from the 5-phase method simulation

Comparison of table 5.7 with table 5.8 shows a significant difference between the UDI values obtained from the 3-phase method simulation and that of 5-phase simulation. This dissimilarity in UDI values could be due to the fact that the 3-phase method do not model direct sun distribution accurately. Transmission matrices could also be responsible for the extensive difference between the 3-phase and 5-phase method results.

In the three-phase method, BSDF data was generated using LBNL's Window program, while in the five-phase method the BSDF data was created with Radiance's "genBSDF" tool. The LBNL Window program computes the BSDF data with radiosity method and may not be appropriate for specular objects such as glass louvers. Whereas, Radiance's genBSDF tool performs forward raytracing to compute the transmission matrices. Also, modeling a translucent glass as a horizontal shading device is not provisioned in the Window program, therefore translucent LC was modeled as regular glass in the 3-phase method. Overall, the 5-phase simulation results seem more reliable and are used to differentiate the shading system's performances.

It can be observed in figure 5.11 that motorized louvers are most successful in providing daylight levels within the 200 to 2000 lux range in the room in all cities. However, the difference between the systems is more noticeable in Seattle and Milwaukee than in sunny climates. Especially in Phoenix, the four systems' average UDI are very close, meaning that the use of dynamic shading devices in such climate is not economic, as a fixed louver system reveal comparable results.

Figures 5.12 to 5.16 show UDI values at sensor points calculated through the 5-phase method simulation for each city. Here too, the difference between the shading systems is more sensible in Seattle and Milwaukee compared to Dallas, San Francisco,

and Phoenix. The motorized louvers provide the highest UDI values among the four alternatives in Seattle and Milwaukee.

5.4.2. Daylight Autonomy

The next metric calculated from the annual illuminance data was Daylight Autonomy (DA) with a minimum threshold of 300 lux. Daylight Autonomy is defined by Reinhart (2002) as "the percentage of occupied times of the year when a minimum work plane illuminance threshold of 300 lux can be maintained by daylight alone". This metric is especially useful when calculating the electric light usage in spaces equipped with automatic lighting controls. Table 5.9 compares shading systems' average DA in the room resulted from the 5-phase method simulations.

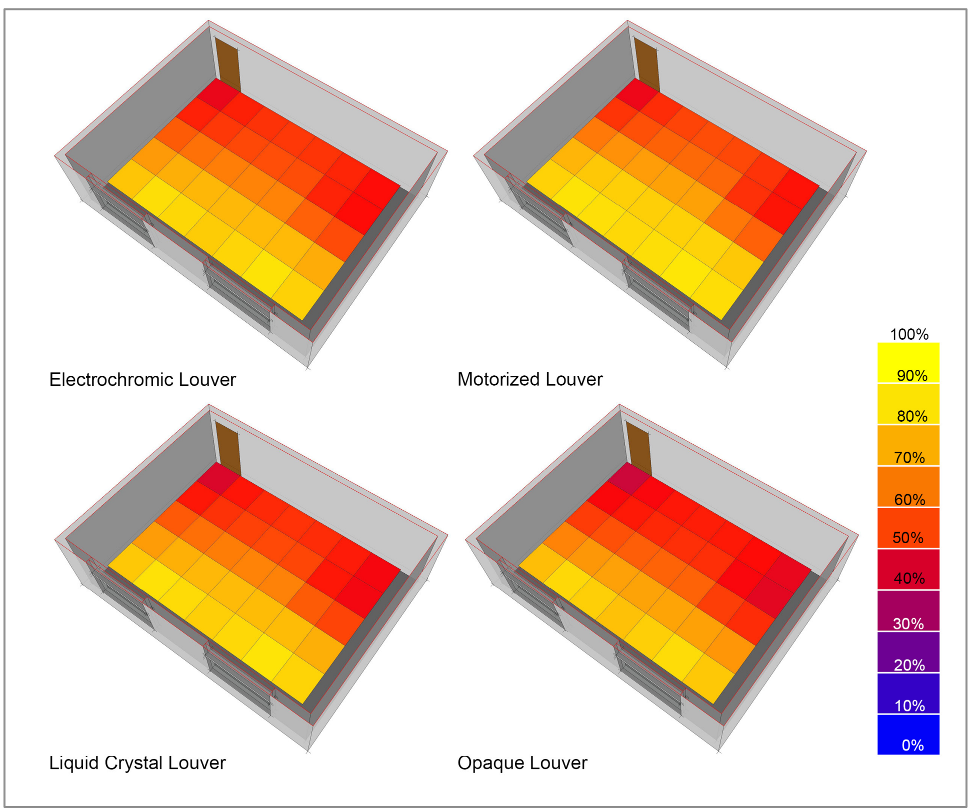


Fig. 5.12: UDI(200-2000) results for Seattle.

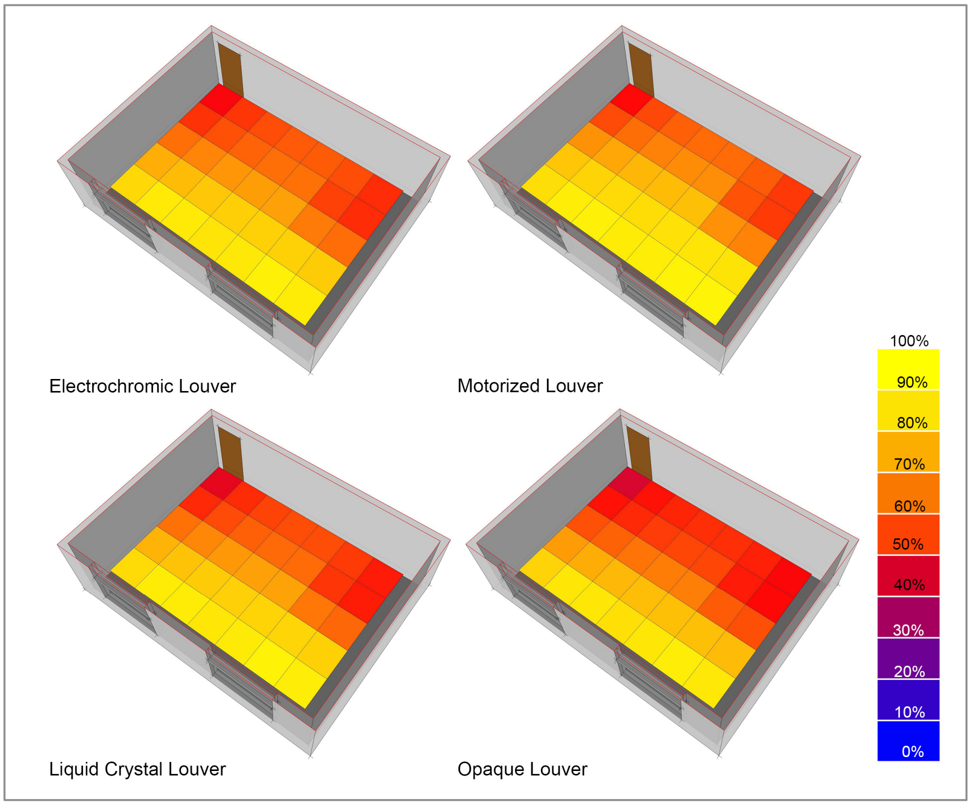


Fig. 5.13: UDI(200-2000) results for Milwaukee.

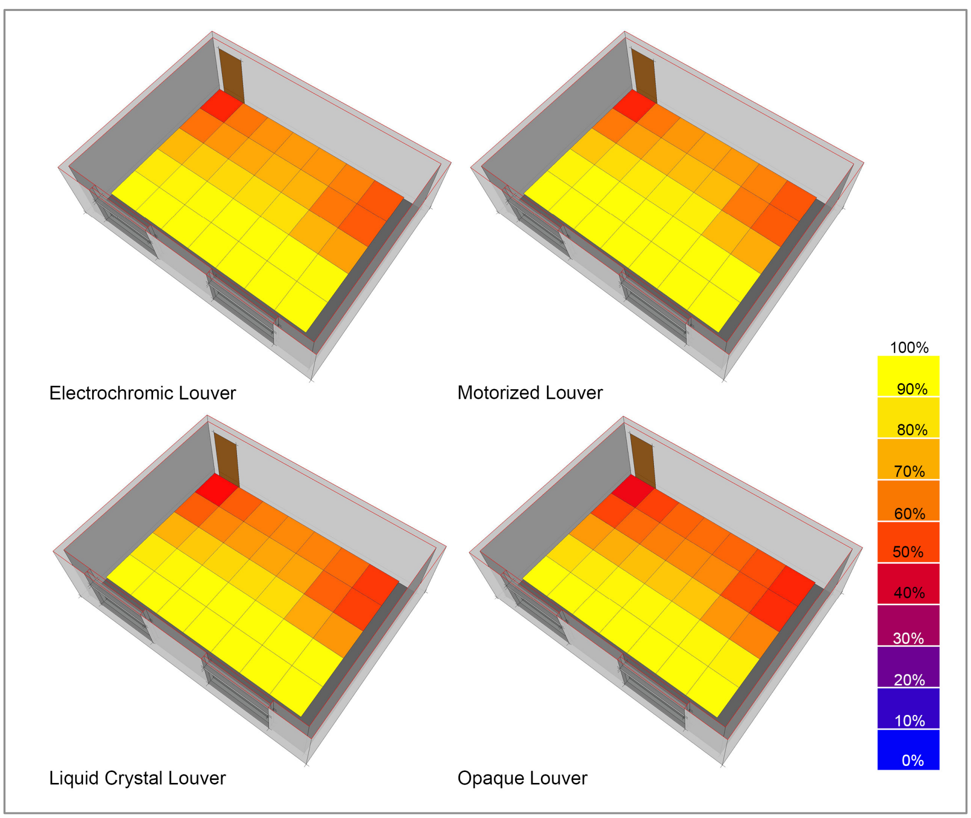


Fig. 5.14: UDI(200-2000) results for Dallas.

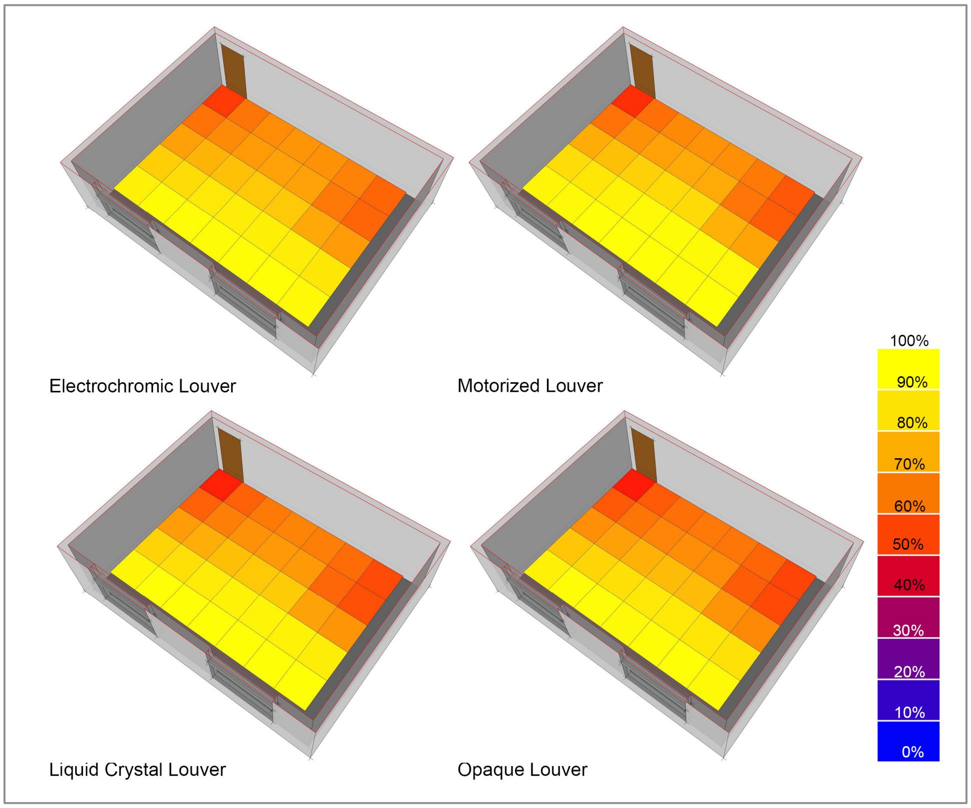


Fig. 5.15: UDI(200-2000) results for San Francisco.

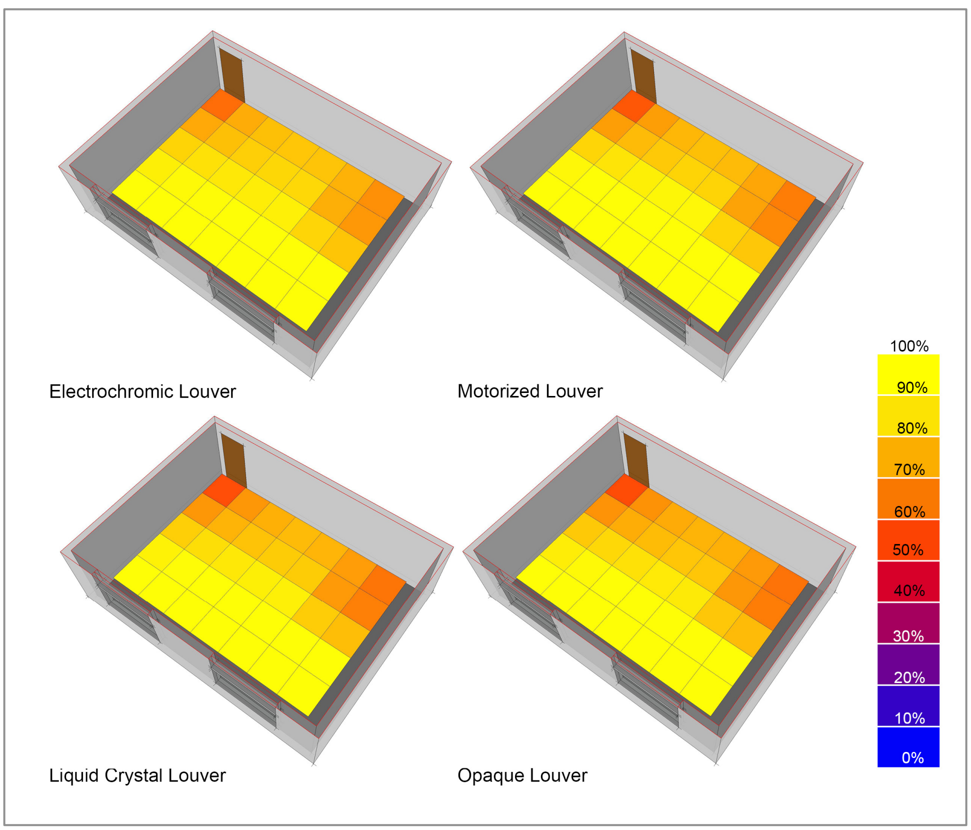


Fig. 5.16: UDI(200-2000) results for Phoenix.

Based on figure 5.17, motorized louvers provide the highest average DA in the room in all cities except for Phoenix. In Phoenix, the average DA of Electrochromic louver stands slightly above other systems. Similar to the UDI results, the difference between the four alternatives in Phoenix is negligible. This might be due to the city's sunny climate in which the shading devices are activated most of the year. Accordingly a fixed shading device is recommended for this climate type.

Figures 5.18 to 5.22 show DA distribution in the room. In Phoenix and San Francisco, electrochromic louvers admit daylight deeper into the space compared to the rest of the shading systems. However, in Seattle, Milwaukee and Dallas, motorized louver is the most successful system in providing relatively even distribution of daylight across the room.

Table 5.9: Average DA resulted from the 5-phase method simulations

	Opaque Louvers	Liquid Crystal Louvers	Electrochromic Louver	Motorized Louver
Dallas	53.73%	55.47%	57.78%	59.45%
Milwaukee	48.22%	50.70%	52.91%	55.33%
Phoenix	62.62%	62.80%	65.71%	64.68%
San Francisco	55.97%	57.05%	59.82%	59.86%
Seattle	43.99%	46.88%	48.89%	51.37%

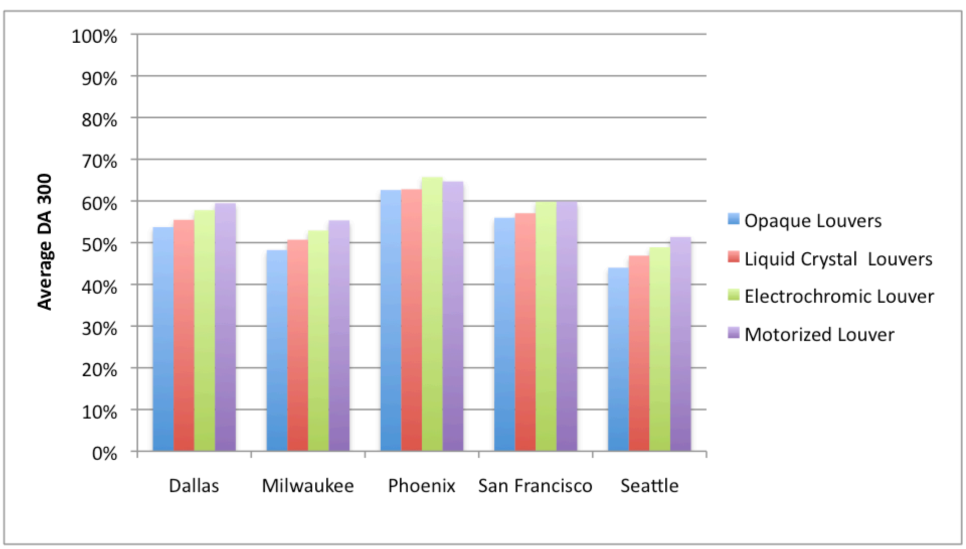


Fig. 5.17: Comparison of shading systems' average DA in the room

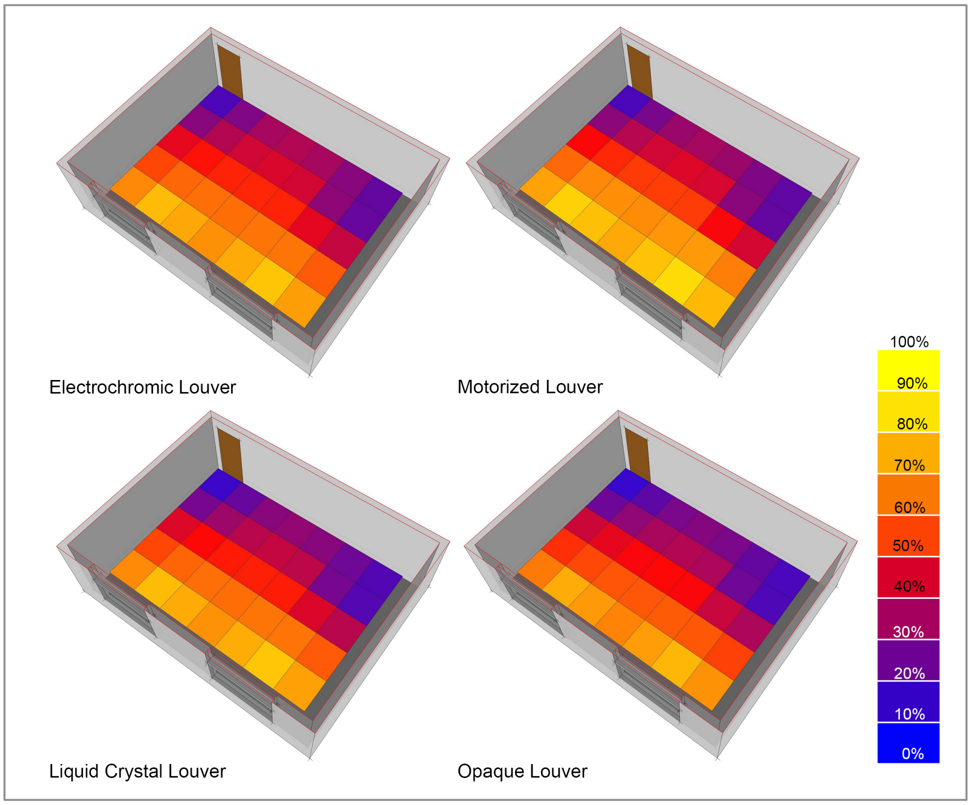


Fig. 5.18: DA results for Seattle

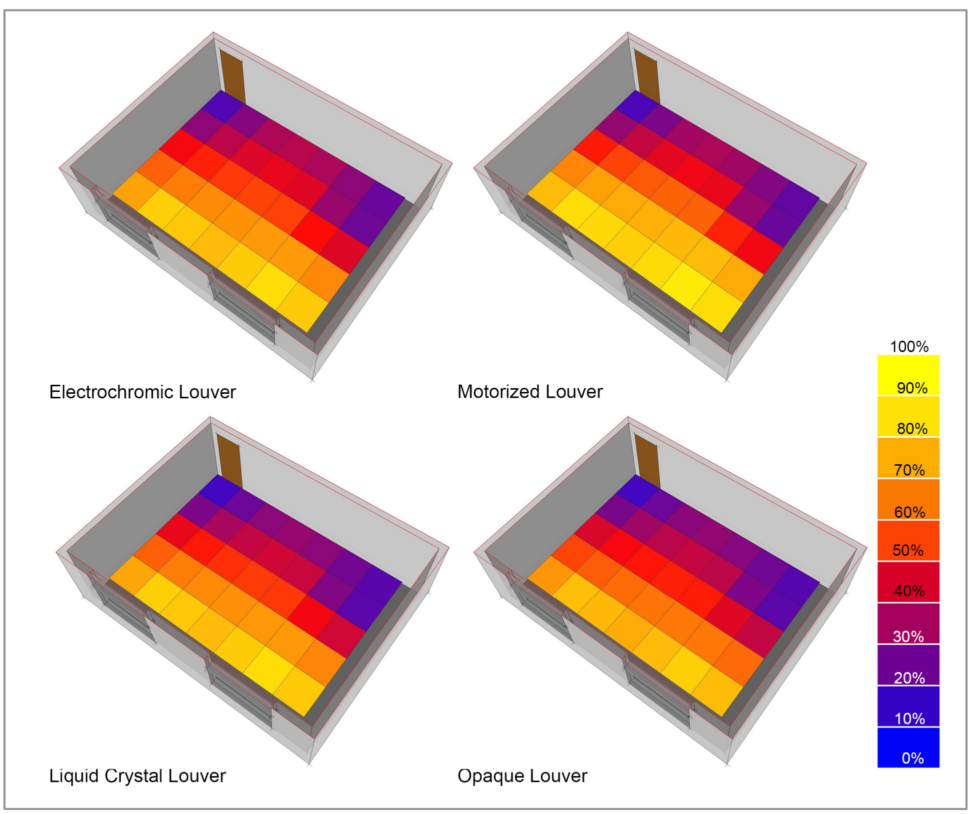


Fig. 5.19: DA results for Milwaukee

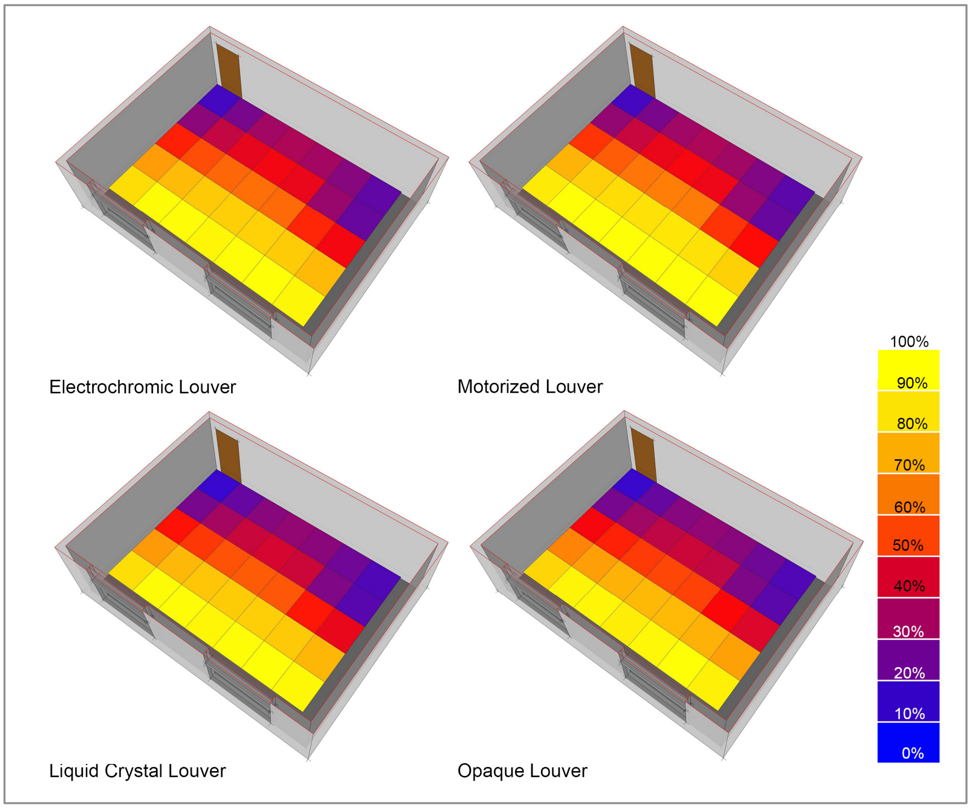


Fig. 5.20: DA results for Dallas

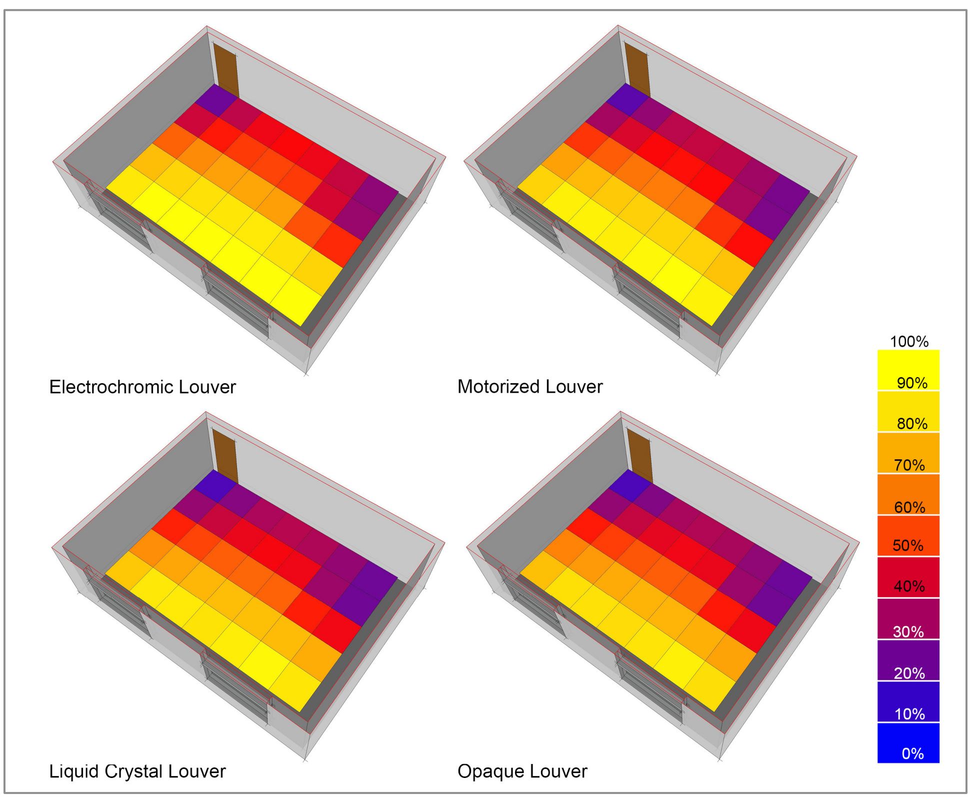


Fig. 5.21: DA results for San Francisco

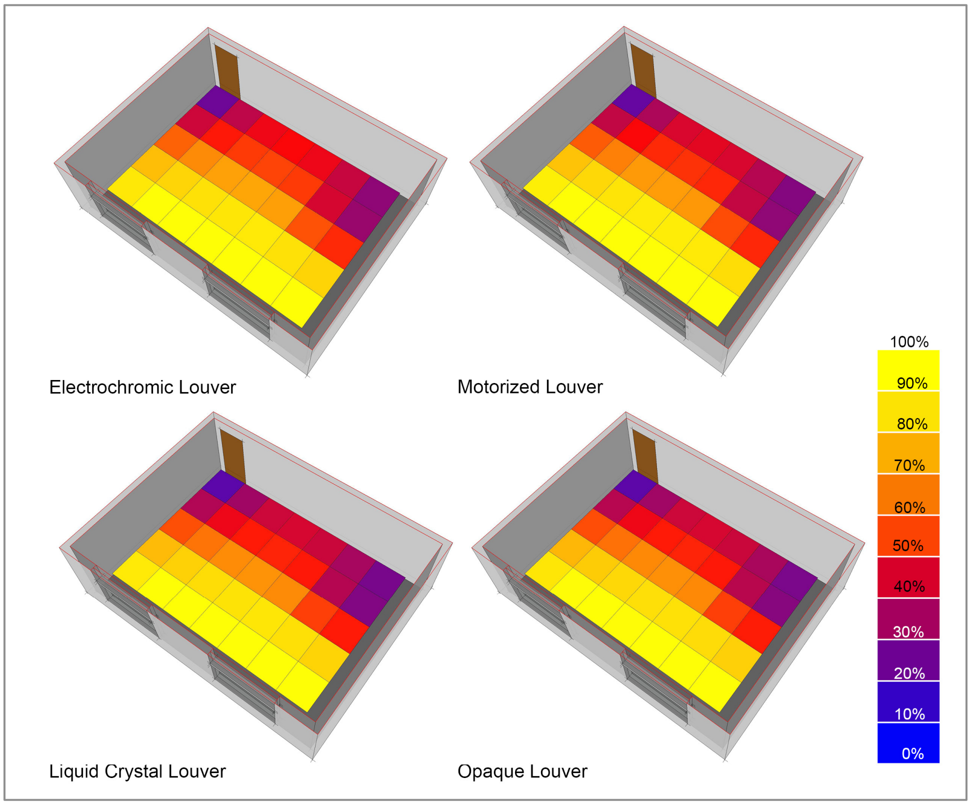


Fig. 5.22: DA results for Phoenix

5.4.3. Glare Metrics

Glare evaluation was performed using the 3-phase method simulations. In the three-phase method it is possible to use a sky vector instead of the sky matrix. Sky vector is generated by genskyvec tool which discretizes the sky dome and converts a single Radiance sky description into a list of RGB values. A sky matrix contains hourly radiance values for each sky patch and is generated from the annual weather data.

12 sky vectors were created each representing a sunny sky on summer solstice, winter solstice, and equinox at 10 am, noon, 2 pm and 4 pm. The glare study was performed only for Milwaukee. The 12 sky vectors with their corresponding shading states resulted in 36 rendered images. Daylight Glare Probability (DGP) and Daylight Glare Index (DGI) was computed for each image using Evlaglare program. Figures 5.23 to 5.25 show the 36 rendered images.

In Evalglare, it is possible to identify the potential sources of glare based on the average scene luminance, the average task luminance, or an absolute threshold. In this study the first two criteria were used to distinguish the glare source. In the first criterion, any pixels with luminance levels above 7 times the scene average luminance is identified as glare source. In the second criterion, any part of the image with luminance values above 4 times the task luminance is considered as a potential source of glare.

Evalglare calculated the glare metrics for the areas of the image that meet above criteria. Table 5.10 shows the resultant DGP and DGI values. A DGP value of 0.35 or higher represents glare sensation. The glare perception threshold for DGI is 18. Based on table 5.10, no serious glare is caused by any of the shading designs. All DGP values are below the glare perception threshold, while DGI detected a few incidents of glare sensation in winter afternoons. Fig 5.26 shows check-files produced by Evalglare. The colored areas demonstrate potential sources of glare detected according to the defined criteria. The blue circle in the middle is the task area.

5.5. ENERGY SAVING POTENTIAL OF SHADING SYSTEMS

To estimate the design option's annual energy performance, the electric light usage in the room as well as the automatic shading devices' own energy use was calculated.

5.5.1. Electric Light Usage

The model assumes two rows of 2-lamp T8 (32 Watt) fluorescent luminaires with 2800 lumen output per lamp. Equation 5.6 was used to calculate the number of required luminaires and their total electric power demand. The electric lights were assumed to be automatically controlled by two separate photocells located in front and back of the room.

Table 5.10: Glare metrics calculated with Evalglare

Upper Shading System	Date	Time	DGP		DGI	
			1st criteria	2nd criteria	1st criteria	2nd criteria
Liquid Crystal Louver	21-Jun	10 AM	0.089689	0.091067	13.048305	13.309432
		12 PM	0.149397	0.149397	14.531952	14.531952
		2 PM	0.1106	0.112035	13.732138	13.974562
		4 PM	0.06746	0.068996	13.401776	13.616178
	21-Sep	10 AM	0.213552	0.213552	17.133383	17.133383
		12 PM	0.225379	0.225379	18.036057	18.036057
		2 PM	0.22127	0.22127	17.795555	17.795555
		4 PM	0.164046	0.164046	16.340809	16.340809
	Dec 21	10 AM	0.22531	0.225175	17.77161	17.762342
		12 PM	0.235392	0.235314	18.744837	18.768787
		2 PM	0.294247	0.294134	21.613176	21.623846
		4 PM	0.186468	0.186468	17.006136	17.006136
Motorized & Fixed Opaque Louver	21-Jun	10 AM	0.077489	0.079632	12.818693	13.272988
		12 PM	0.121253	0.123088	13.724708	14.045823
		2 PM	0.096586	0.098751	13.50719	13.972103
		4 PM	0.059694	0.061826	13.141933	13.743939
	21-Sep	10 AM	0.164421	0.164421	14.232192	14.232192
		12 PM	0.193846	0.193846	14.944402	14.944402
		2 PM	0.190675	0.190675	15.299716	15.299716
		4 PM	0.116261	0.116362	14.966277	14.979715
	Dec 21	10 AM	0.192325	0.193043	13.547145	13.546644
		12 PM	0.206869	0.206845	15.068111	15.086176
		2 PM	0.288064	0.288469	19.683764	20.469007
		4 PM	0.166404	0.166704	16.399355	16.368713
Electrochromic Louver	21-Jun	10 AM	0.056064	0.056466	13.691846	13.666658
		12 PM	0.081582	0.08175	14.303596	14.150625
		2 PM	0.071053	0.071203	14.293975	14.126957
		4 PM	0.047047	0.050413	12.619766	14.095975
	21-Sep	10 AM	0.076685	0.076915	13.40579	13.273129
		12 PM	0.109218	0.109173	13.617506	13.546835
		2 PM	0.119579	0.122895	13.676772	14.557565
		4 PM	0.070724	0.073948	14.301332	15.010801
	Dec 21	10 AM	0.105196	0.104851	10.851161	10.503579
		12 PM	0.151328	0.151127	13.19581	13.082761
		2 PM	0.287852	0.287689	19.940237	20.269522
		4 PM	0.145485	0.14591	16.331392	16.18907

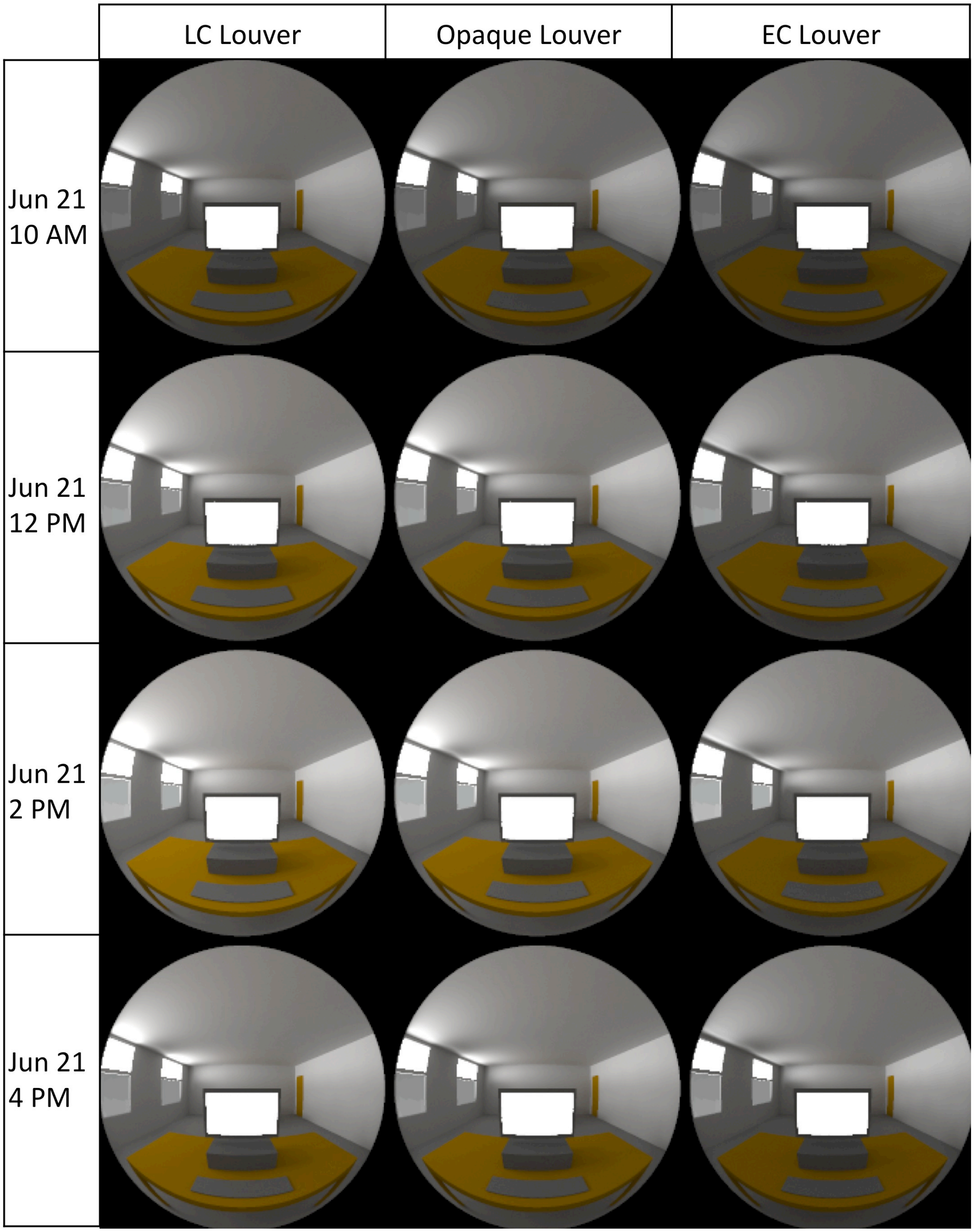


Fig. 5.23: Rendered images produced through the 3-phase simulations for Milwaukee on summer solstice.

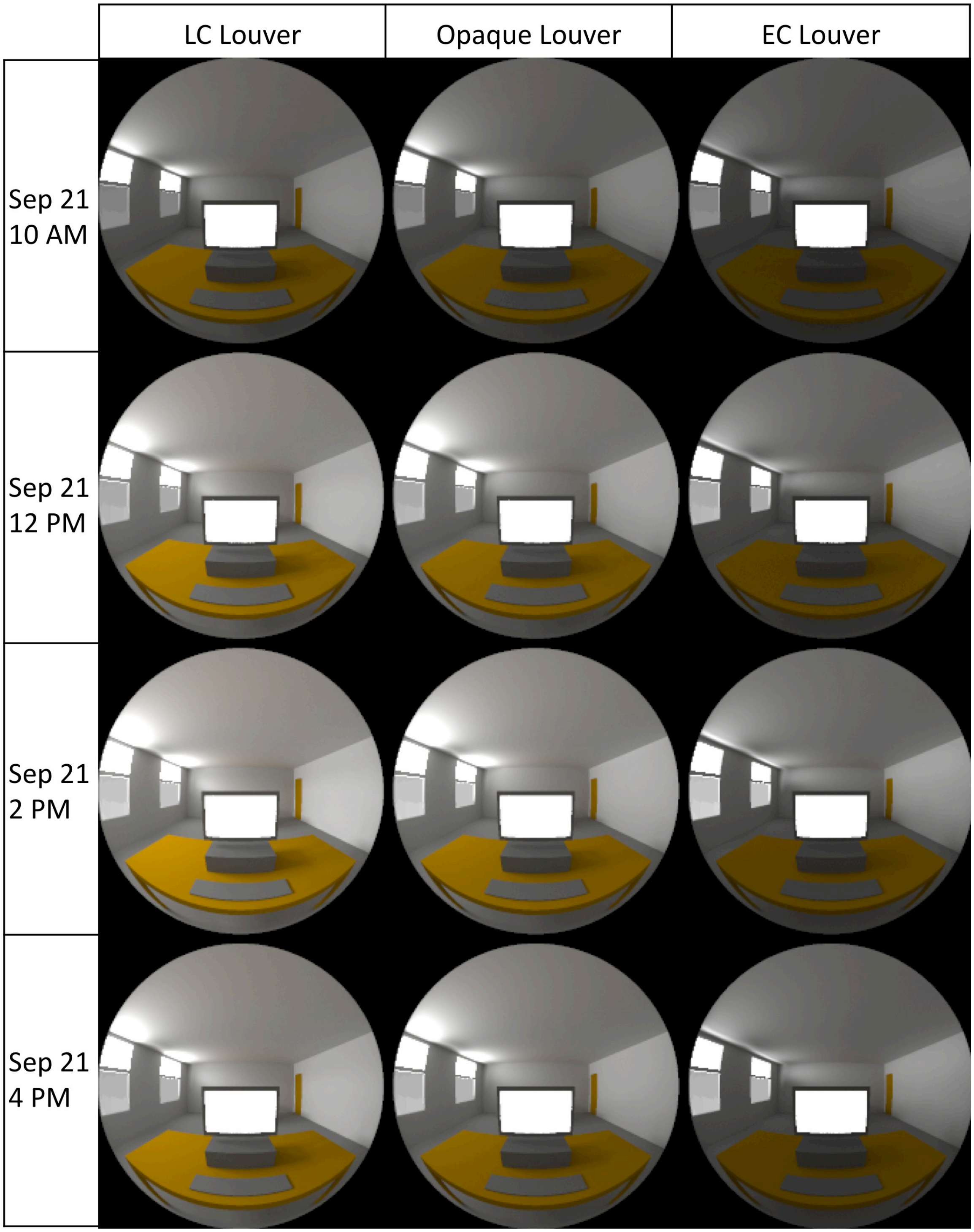


Fig. 5.24: Rendered images produced through the 3-phase simulations for Milwaukee on equinox.

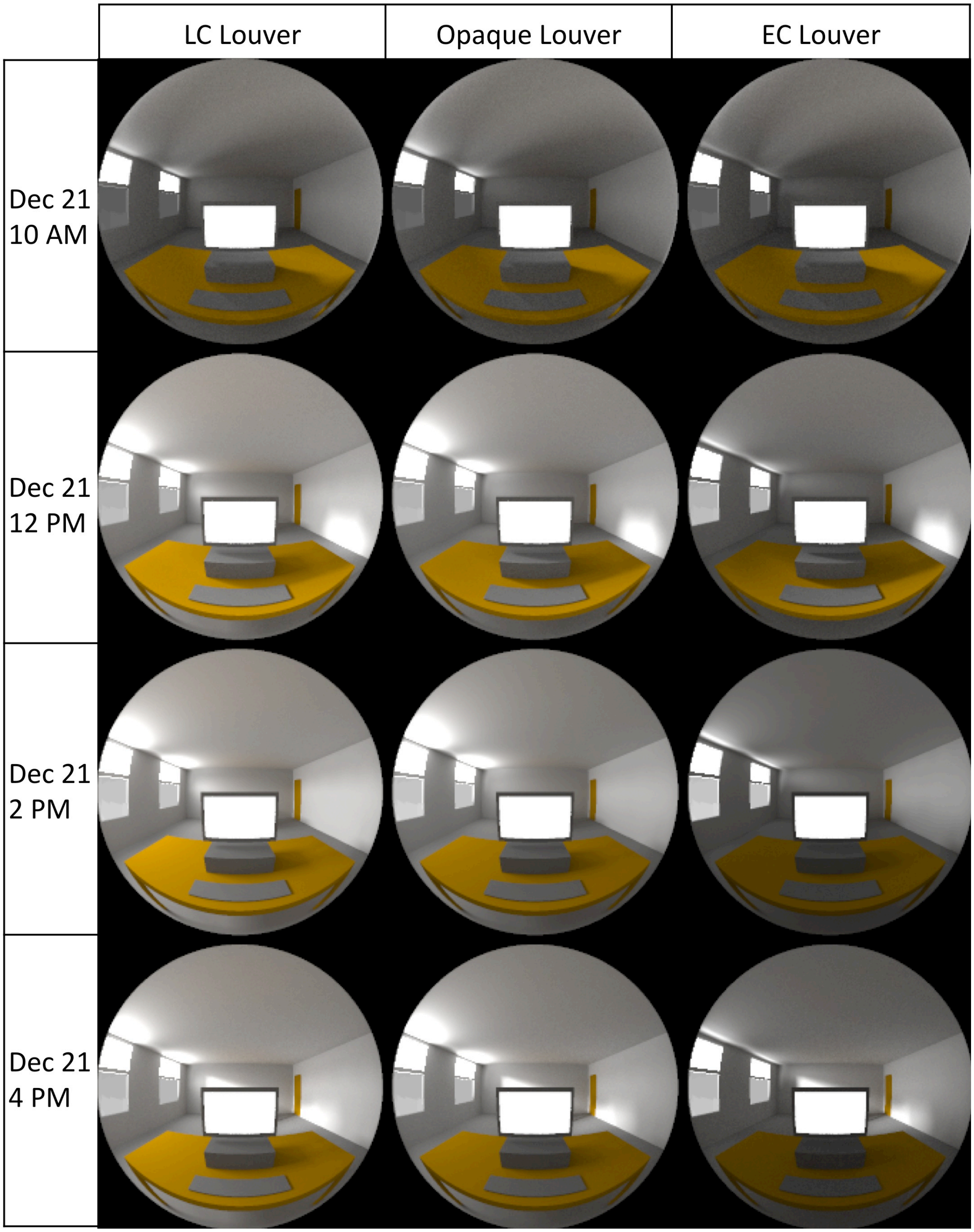


Fig. 5.25: Rendered images produced through the 3-phase simulations for Milwaukee on winter Solstice.

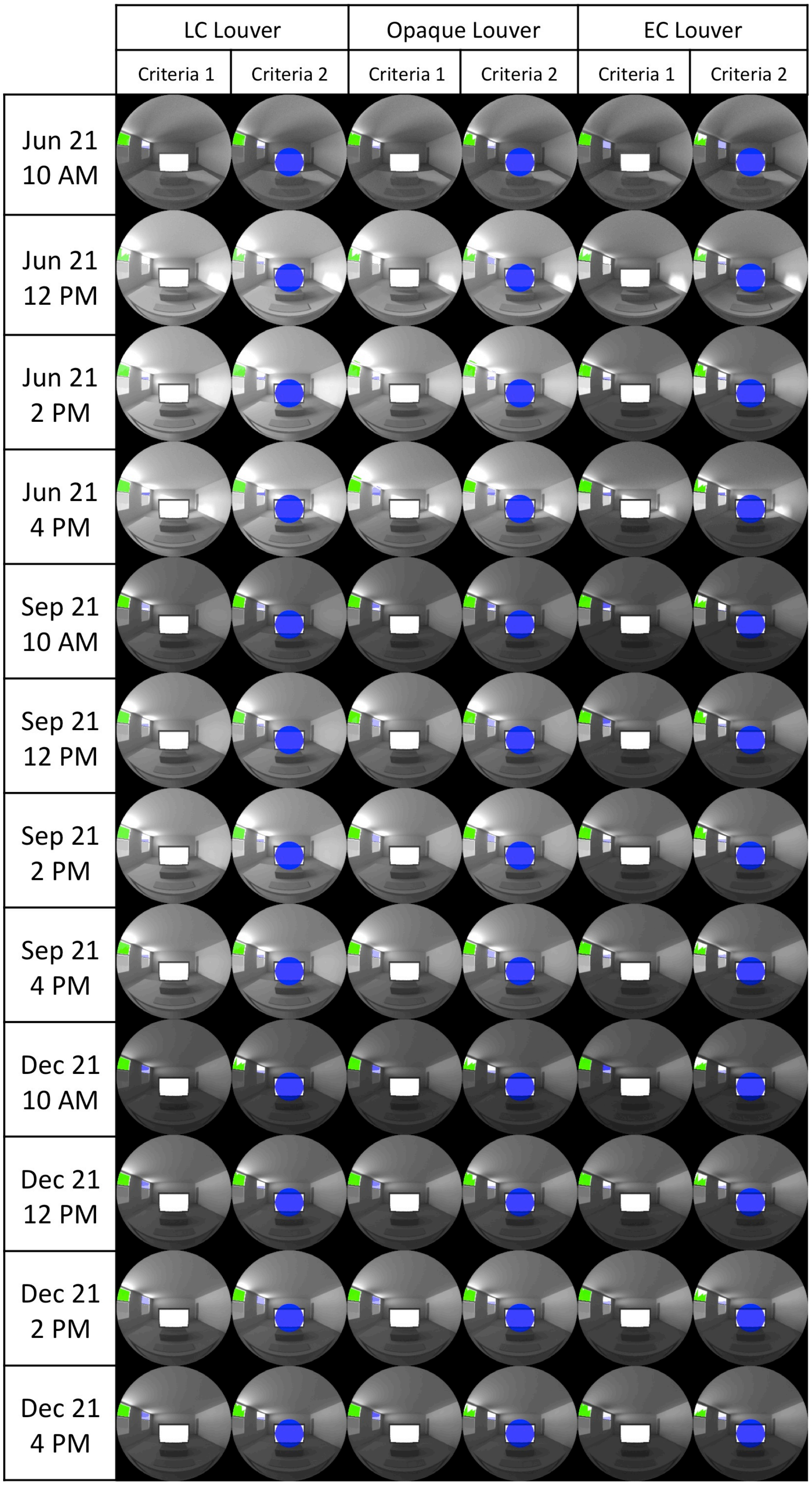


Fig. 5.26: Evalglare check files. The blue circle is the task area. Other colored areas are where criteria 1 and 2 is met.

Tables 5.11 and 5.12 show the number of hours when the front and back rows of luminaries need to be turned on respectively throughout the annual occupied hours. The values in these two tables were obtained by counting the number of hours when the illuminance level was below 300 lux at two sensor points, one located blew the first row of luminaires and the other located below the second row of the luminaries from the window. To calculate the annual electric light usage, the corresponding values in tables 5.11 and 5.12 were summed and multiplied by 192 watts, the electric power demand of one row of luminaires. Table 5.13 shows the resultant values.

Equation 5.6: Calculation of the electric lighting energy demand

Number of luminaires required = (Desired illuminance x Area of room) / (Lumens x LLF x CU)

where:

Lumens: lumens per luminaire
LLF: light loss factor
CU: coefficient of utilization

As a rule of thumb we can use: CU x LLF=0.5
If we use 2-lamp T8 (32 Watt) fluorescent luminares with 2800 lumen output per lamp:

$$N = (300 \times 48) / 2800 \times 2 \times 0.5 = 5.14 \text{ luminaires}$$

$$6 \times 2 \text{ lamps} = 12 \text{ lamps}$$

Total electric lighting power demand:

$$32 \text{ watts} \times 12 = 384 \text{ watts}$$

Table 5.11: Number of occupied hours when illuminance level is below 300 lux at sensor 12. Sensor 12 is located below the first row of luminaires from the window.

	Opaque Louvers	Liquid Crystal Louvers	Elechtrochromic Louvers	Motorized Louvers
Dallas	304	240	241	145
Milwaukee	792	640	642	495
Phoenix	192	166	165	128
San Francisco	419	358	360	266
Seattle	969	842	850	669

Table 5.12: Number of occupied hours when illuminance level is below 300 lux at sensor 36. Sensor 36 is located below the second row of luminaires from the window.

	Opaque Louvers	Liquid Crystal Louvers	Elechtrochromic Louvers	Motorized Louvers
Dallas	2345	2335	2163	2152
Milwaukee	2342	2333	2113	2156
Phoenix	1892	1888	1674	1805
San Francisco	2152	2115	1909	2026
Seattle	2448	2360	2162	2229

Table 5.13: Annual electric light usage (Wh) in the room.

	Opaque Louvers	Liquid Crystal	Elechtrochromic Louvers	Motorized Louvers
Dallas	508608	494400	461568	441024
Milwaukee	601728	570816	528960	508992
Phoenix	400128	394368	353088	371136
San Francisco	493632	474816	435648	440064
Seattle	656064	614784	578304	556416

5.5.2. The Energy Consumption of Automatic Shading Devices

In order to estimate systems' total electricity usage, we need to take into account the shading devices' own electric power demand. Equations 5.7 to 5.9 calculate the power demand of each dynamic shading device. Table 5.14 displays the number of hours or times per year when the automatic shading devices need to be activated and their corresponding total electricity use. As discussed earlier, electrochromic glass louvers use electricity in their tinted state. Therefore, the annual sunny hours (values in column two) represent the number of hours when electrochromic louvers consume electricity.

By multiplying column 2 values by 9.04 watts, the annul electricity usage of the electrochromic louvers were obtained. The LC louvers use electricity to maintain a clear state. Accordingly the annual cloudy hours during the occupied times (column 3) were multiplied by 30.14 Watts (power demand) to calculate the annual electricity consumption of LC louver in each city. In terms of motorized louvers, the annual number of adjustments were calculated from the weather data and multiplied by 0.49 Wh.

Equations 5.7 to 5.9: Calculation of the dynamic shading devices' energy demand

Liquid crystal glass uses 0.5 watts per square feet of glass in its clear state.
Electrochromic glass uses 0.15 watts per square feet of glass in its tinted state.
The room has two windows. There are 14 louvers in each window, each measuring 0.1 by 2 meters.

Switchable louver area:

$$14 \times 0.1 \times 2 \times 2 = 5.6 \text{ square meter}$$
$$5.6\ m^2 \times 10.764 = 60.28 \text{ sqft}$$

LC louver power demand: $60.28 \times 0.5 = 30.14$ *Watts (Clear state)*

EC louver power demand: $60.28 \times 0.15 = 9.04$ *Watts (Tinted state)*

Motorized louver's motor Specification: 110 V AC, 126 Watts, 2in/sec lift speed

The upper window height: 28 inches
$$28 / 2 = 14 \text{ sec}$$
$$126 \text{ Watts} \times 15\text{sec} = 126 \times 14/3600\ h = 0.49 \text{ Wh per lift}$$

Motorized louver power demand: 0.49 Wh per lift

Table 5.14: Annual electricity consumption of automatic shading devices.

	Annual sunny hours	Annual cloudy hours	Motorized louver movements	EC louver Annual Electricity Usage (Wh)	LC louver Annual Electricity Usage (Wh)	Motorized Louver Annual Electricity Usage (Wh)
Dallas	2451	834	360	22157	25137	176
Milwaukee	2073	1212	442	18740	36530	217
Phoenix	2970	315	215	26849	9494	105
San Francisco	2620	665	411	23685	20043	201
Seattle	1886	1399	599	17049	42166	294

5.5.3. Total Electricity Consumption

Table 5.15 shows the total electricity consumption of each subdivided window design. The values in table 5.15 are the sum of annual electric light usage in the room and automatic shading devices' energy consumption. Regarding the opaque louvers the values are the electric light usage only as the louvers don't consume electricity themselves. Figure 5.27 is the graphical representation of table 5.15. It can be observed in figure 5.27 that motorized louvers reveal the least amount of energy use among the

four upper shading alternatives. Once again, the difference between the design options is most evident in Seattle and Milwaukee and least significant in Phoenix.

Compared to the base case, which is the subdivided window with fixed louvers, motorized louvers reduce the energy use by 100 kWh per year. It is important to note that these values are only for one room, and need to be scaled for large buildings with multiple rooms. The next successful option is the subdivided window with electrochromic glass louver on the upper section. Liquid crystal glass louvers have the highest total electricity use due to the device's high energy demand.

Table 5.15: Total electricity consumption of each shading design (kWh).

	Opaque Louvers (kWh)	Liquid Crystal Louvers (kWh)	Elechtrochromic Louvers (kWh)	Motorized Louvers (kWh)
Dallas	509	520	484	441
Milwaukee	602	607	548	509
Phoenix	400	404	380	371
San Francisco	494	495	459	440
Seattle	656	657	595	557

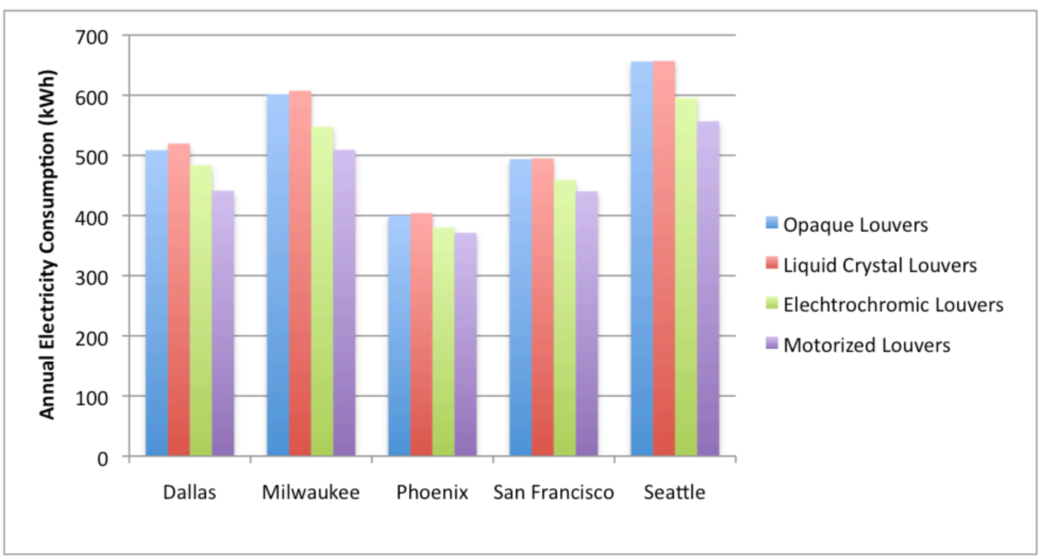


Fig. 5.27: Total annual electricity consumption of the design options

5.6. DISCUSSION AND CONCLUSION

This chapter examined daylight and energy performance of a number of design options for a subdivided window. Among the studied options, a subdivided window with occupant-controlled venetian blinds on the lower part and motorized louvers on the upper part proved most efficient in terms of both daylight sufficiency and electricity consumption. The same subdivided window with electrochromic glass louvers on the upper section of the window ranked second in this evaluation. The study of the systems in different climates however showed that dynamic shading devices are not justifiable in sunny climates and are suitable for cloudy climates only.

Despite its slightly inferior performance, the electrochromic glass louver could still be considered as an option, in that it alternates from one state to another quietly. Whereas, with motorized louver the change is more sensible due to motor noise and slat movement. Therefore, in cases where electricity is provided on-site through PV panels, it might be reasonable to use EC glass louver in subdivided windows.

CHAPTER 6
Redesigning Studio 406 Windows

Chapter 5 evaluated a few design options for subdivided windows. It was concluded that a subdivided window with motorized louver system on the upper part and occupant-controlled venetian blinds on the lower part of the window would be an ideal solution for Milwaukee climate. In this chapter, the subdivided windows of chapter 3 are redesigned with motorized louvers, and the daylight performance of the system is evaluated using Radiance simulation.

6.1. EXTERIOR AND INTERIOR MOTORIZED LOUVERS

Previously, the field study of subdivided windows with fixed upper louvers demonstrated a good potential for an occupant favorable daylight control system. However, to provide equal level of satisfaction for core and perimeter area occupants, a dynamic upper shading device was suggested. Based on the chapter 5 findings, the subdivided windows in studio 406 of the UWM Architecture school were redesigned with exterior and interior motorized louvers. The following compares the annual daylight performance of the systems with that of the original windows using Radiance simulation. The original windows in the architecture school are undivided windows with occupant-controlled venetian blinds installed at the window head. The thermal performance of the exterior and interior shading designs were also studied using Trnsys program.

6.1.1. The Exterior Shading System

The exterior shading design consists of automatically controlled retractable louvers at the exterior of the upper part of the window, a light shelf, and occupant-controlled venetian blinds on the interior of the lower part of the window. The upper

louvers are angled at 45 degrees. Since the main façade is facing west, horizontal slats would not control the low angle sun penetration. The projection depth of the lightshelf is 1 meter on west and 0.5 meter on the south façade. The automatic louvers in this system move top-down. Figure 6.1 displays the exterior shading design in two states.

6.1.2. The Interior Shading System

Similar to the exterior shading system, the interior shading includes venetian blinds on the lower part of the window and automatically controlled shading devices at the upper part of the window, only the automatic louvers are installed on the interior side of the window, and there is no lightshelf. Here too the upper slats are angled at 45 degrees. The automatic louvers in this system move bottom-up to keep the top of the windows clear for maximum daylight penetration at low daylight conditions. Figure 6.2 displays the interior shading design along with the existing window design.

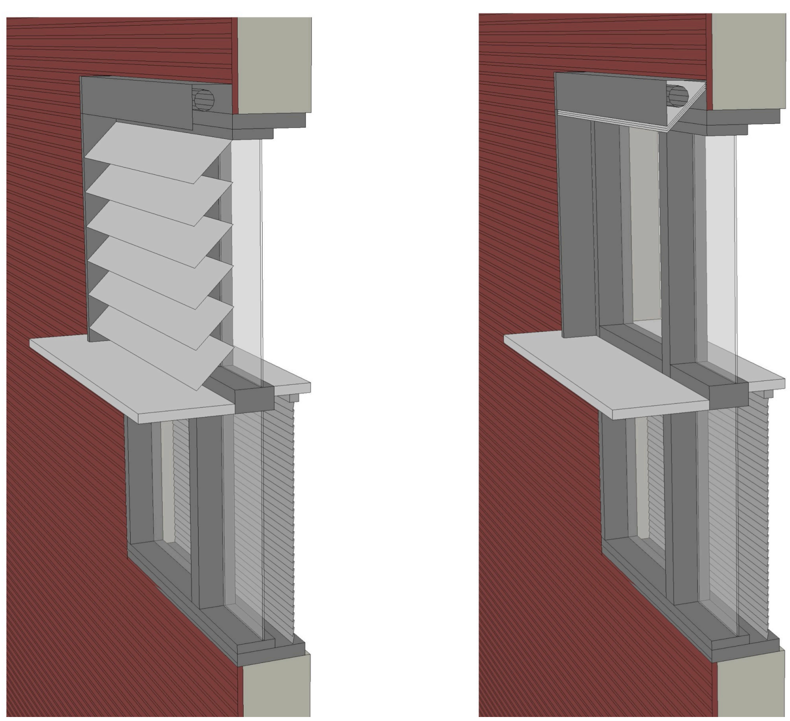


Fig. 6.1: Subdivided window with dynamic exterior shading

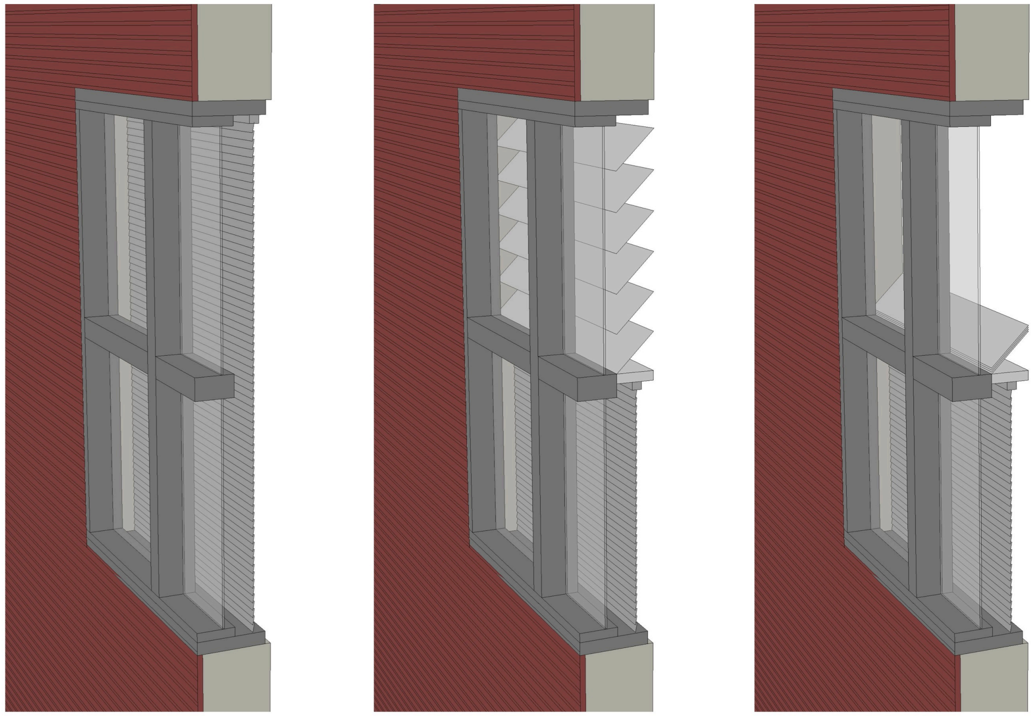


Fig. 6.2: The existing window (left) and the subdivided window with interior dynamic shading in closed (middle) and open state (right).

6.2. SIMULATING THE SHADING SYSTEMS WITH RADIANCE

The three window designs were simulated through the five-phase method described in chapter 5. The Radiance simulations resulted in annual hourly illuminance data and hourly rendered images, which were subsequently used to calculate dynamic daylight metrics and glare indices.

6.2.1. Model Description

A detailed model of the room and the neighboring buildings was created in Ecotect. Then the model was saved in Radiance geometry format. The rest of the simulation was carried out in Radiance. For accurate results, material reflectances were measured using a Gossion luminance meter and an 18%-reflectance grey card. Table 6.1 shows the resultant material properties. For illuminance evaluations, 40 sensor points were defined in the room each representing the middle point of a desk (Figure 6.3).

Table 6.1: The reflectance and visible transmittance of materials in studio 406

Material	Reflectance or Visible Transmittance	Material	Reflectance
Interior Walls	68%	Louvers	75%
Window Glass	VT: 73%	Exterior Walls	30%
Aluminum Window Frame	51%	Desks	67%
Ceiling	68%	Concrete Columns	39%
Floor	27%	Light Fixtures	80%
Venetian Blind Slats	50%	Divider Walls	60%
HVAC Ducts	40%	Ground	30%
Exterior Lightshelf	75%	Roofs	40%

As described in chapter 3, studio 406 has windows in three different orientations. The two proposed window designs were modeled as west and south facing windows, while the north windows remained in their original design. Similar to the subdivided windows in chapter 5, venetian blinds and automatic louvers were on separate control algorithms. Therefore, the 3 shading systems resulted in 32 different scenarios to be modeled in Radiance (Table 6.2). A full year simulation was performed for each scenario. Then the control algorithms were used to filter and consolidate the illuminance data and rendered images. Finally, annual daylight performance metrics were computed from the filtered data. The 5-phase simulation process is discussed in more detail in Appendix E.

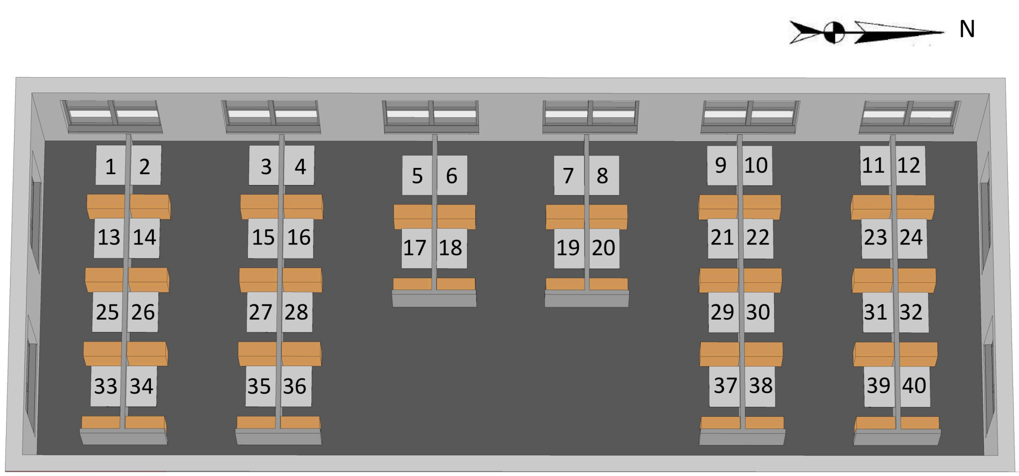


Fig. 6.3: The sensor locations at studio 406.

Table 6.2: Radiance modeling scenarios

Scenario	Shading System	South Louvers	South Venetian Blinds	West Louvers	West Venetian Blinds
1	Exterior louvers	Open	Open	Open	Open
2	Exterior louvers	Open	Open	Open	Closed
3	Exterior louvers	Open	Open	Closed	Closed
4	Exterior louvers	Open	Closed	Closed	Closed
5	Exterior louvers	Closed	Closed	Closed	Closed
6	Exterior louvers	Closed	Closed	Closed	Open
7	Exterior louvers	Closed	Closed	Open	Open
8	Exterior louvers	Closed	Open	Open	Open
9	Exterior louvers	Open	Closed	Open	Closed
10	Exterior louvers	Closed	Open	Closed	Open
11	Exterior louvers	Closed	Open	Closed	Closed
12	Exterior louvers	Closed	Closed	Open	Closed
13	Exterior louvers	Open	Closed	Open	Open
14	Exterior louvers	Open	Open	Closed	Open
15	Interior louvers	Open	Open	Open	Open
16	Interior louvers	Open	Open	Open	Closed
17	Interior louvers	Open	Open	Closed	Closed
18	Interior louvers	Open	Closed	Closed	Closed
19	Interior louvers	Closed	Closed	Closed	Closed
20	Interior louvers	Closed	Closed	Closed	Open
21	Interior louvers	Closed	Closed	Open	Open
22	Interior louvers	Closed	Open	Open	Open
23	Interior louvers	Open	Closed	Open	Closed
24	Interior louvers	Closed	Open	Closed	Open
25	Interior louvers	Closed	Open	Closed	Closed
26	Interior louvers	Closed	Closed	Open	Closed
27	Interior louvers	Open	Closed	Open	Open
28	Interior louvers	Open	Open	Closed	Open
29	Existing Design	-	Open	-	Open
30	Existing Design	-	Closed	-	Closed
31	Existing Design	-	Closed	-	Open
32	Existing Design	-	Open	-	Closed

6.2.2. Validating the Radiance model with HDR imaging

To verify the accuracy of the Radiance model, an HDR image was captured inside the studio and was compared to the Radiance rendering of the same view. The HDR image was computed from exposure bracketed images taken with a Canon EOS 5D Mark II camera at night under electric lighting (Figure 6.4). The electric lights were modeled in Radiance using the photometric data (IES file) of existing luminaires. Figure 6.5 shows the two images in real and false colors. The luminance values in the Radiance-rendered image are very close to those in the camera-generated HDR image.

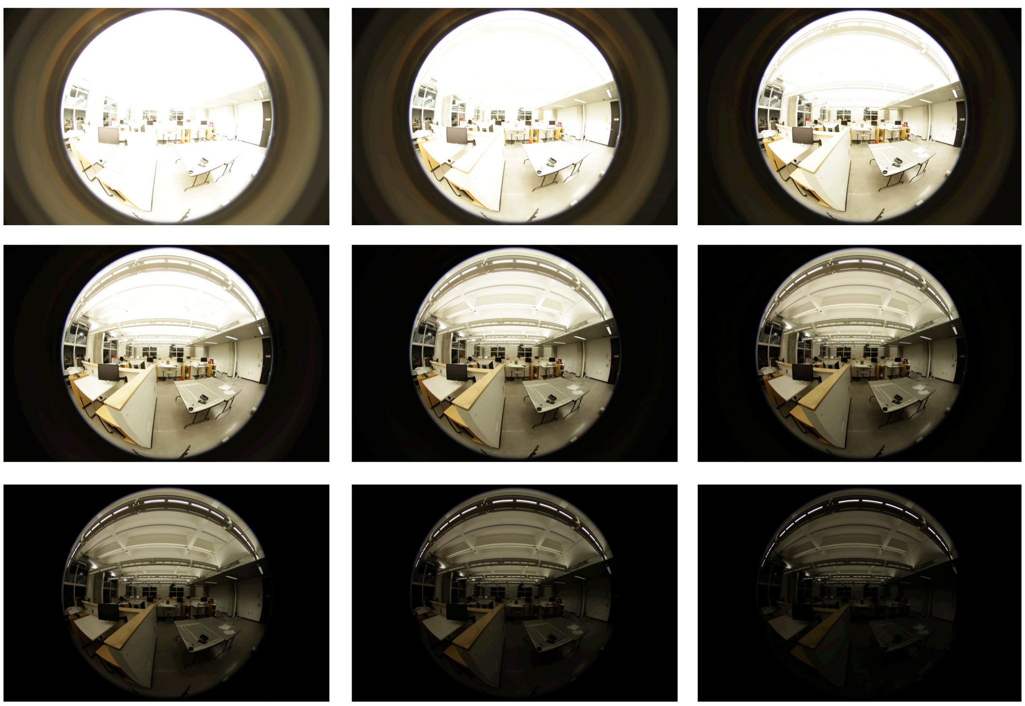


Fig. 6.4: Exposure bracketed images captured at night to compute an HDR image

6.2.3. Running Radiance on Amazon Cloud (AWS EC2)

Due to the huge volume of simulation processes, some parts of the computation was carried out in Amazon Elastic Compute Cloud (AWS EC2). By selecting a high performance instance, hourly annual renderings were performed 16 times faster than on the personal computer, in which it would take about 48 hours for each scenario to be

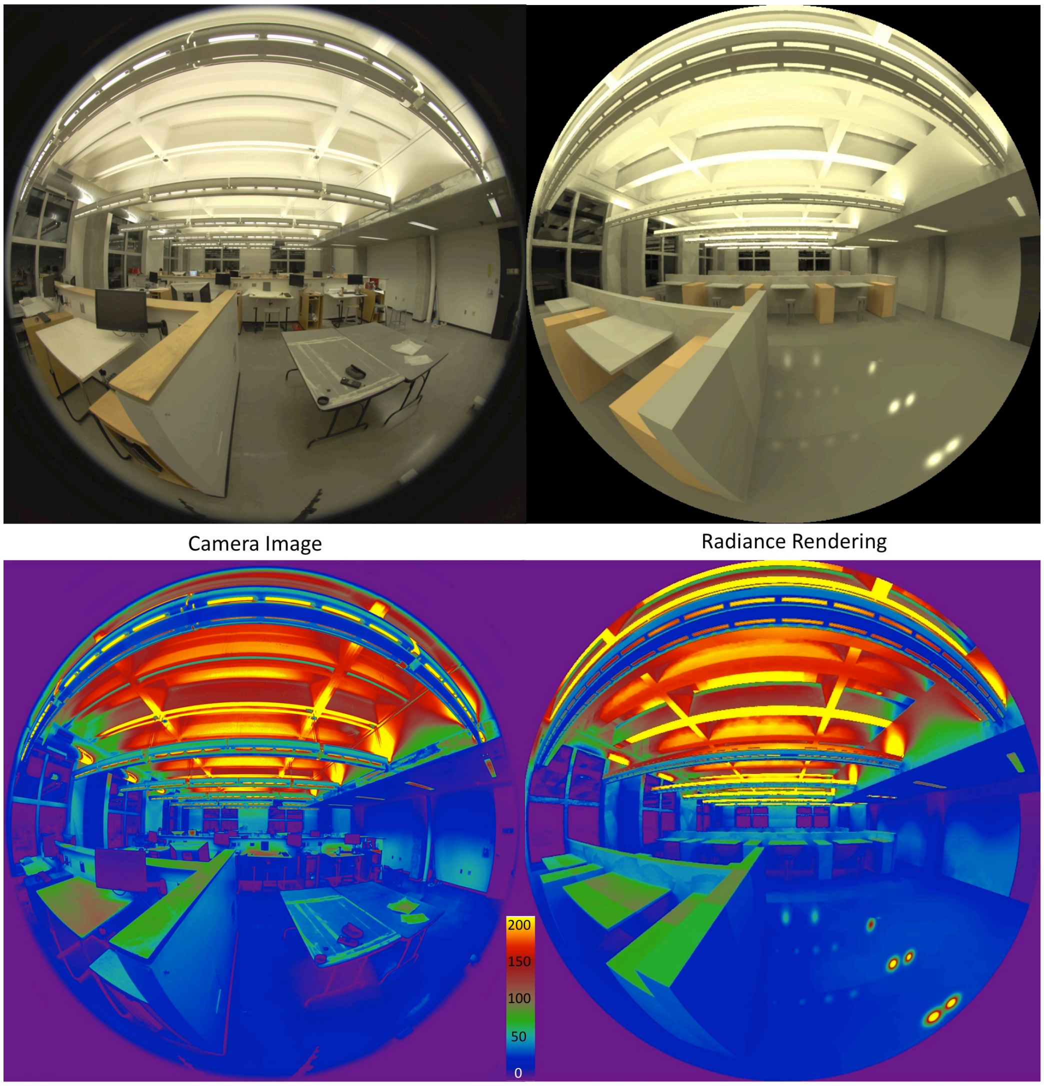


Fig. 6.5: Comparison of the Radiance and camera-generated luminance maps

completed. With cloud computing it was also possible to run several instances in parallel and further accelerate the computation. Another advantage of cloud computing was the extra storage volumes that could be attached to a running instance. More information can be found at Jack de Valpine's (2013) blog post on running Radiance on AWS EC2.

6.3. SHADE CONTROL ALGORITHM

In order to consolidate the 32 sets of annual illuminance data and renderings down to 3 sets, two shade control algorithms were used, one concerning the venetian blinds and the other concerning the motorized louvers.

6.3.1. Control Algorithm for Venetian Blinds

Similar to the previous chapter, Reinhart's (2002) model was used to predict occupant shade control behavior. The model assumes that occupants deploy the venetian blinds when the transmitted solar radiation exceeds 50 W/m2. Once lowered, the shades stay down for the rest of the day and are opened in the next morning. For the existing window design however, two models were defined: the active user and the passive user model. The active user model is as described above, but in passive user model, the shades are adjusted on a weekly basis. The active user mode can be achieved by either encouraging the occupants to open the venetian blinds every morning upon arrival, or adding a spring system to the venetian blinds that retracts the shades overnight.

Due to the complexity of the model and neighboring buildings, transmitted vertical irradiance through the west and south facing windows were obtained using TRNSYS software. The same TMY data used for daylight calculations served as input data for solar radiation calculations in TRNSYS. The height and distance of obstacles were entered in the program along with the window specifications. The result was hourly transmitted solar radiation data for the west and south windows.

6.3.2. Control Algorithm for Automatic Louvers

The control algorithm for automatic shading devices was based on the presence of direct sunlight. It was assumed that the motorized louvers would be expanded when direct normal irradiance was equal or grater than 50% of diffuse horizontal irradiance. They remained in their closed state for at least one hour before reopening. For west facing windows however there was an additional criteria, and that was the time of day. The automatic louvers in west facing windows would be activated in the afternoons only.

6.3.3. Occupancy Schedules

In this analysis, the data was filtered based on daylight hours, because the architecture studios are occupied all day long.

6.4. DAYLIGHT PERFORMANCE RESULTS

Three dynamic daylight metrics of Useful Daylight Illuminance (UDI), Daylight Autonomy (DA), and Maximum Daylight Autonomy (DAmax) were calculated from the hourly illuminance data at sensor points. The hourly images were analyzed with Evalglare program in which Daylight Glare Probability (DGP) was obtained for each image. The results were used in annual visual comfort assessment of the systems.

6.4.1. Useful Daylight Illuminance (UDI)

Figure 6.6 illustrates the average UDI(200-2000) in the room resulted from the five-phase method simulation of the three shading designs. UDI(200-2000) represents the percentage of the occupied hours throughout the year when the illuminance at sensor point is between 200 and 2000 lux. It can be observed that on average, the interior louvers are most successful in keeping indoor daylight within the desired range.

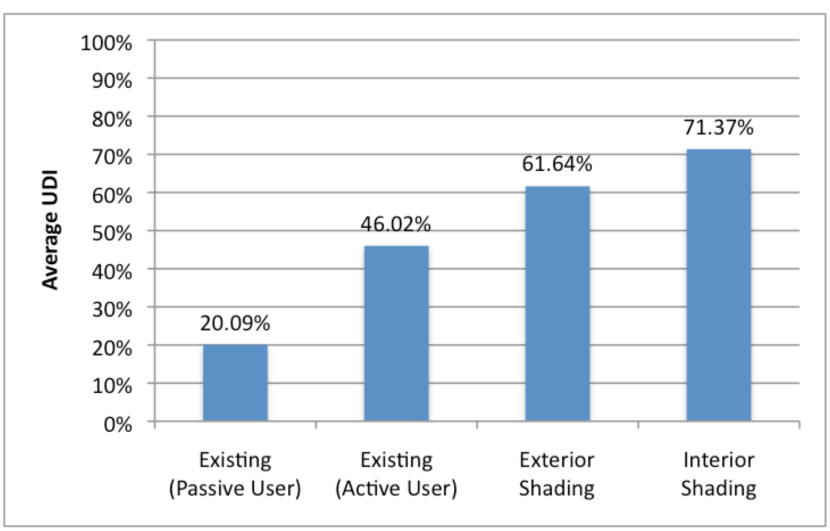


Fig. 6.6: The average UDI in the room with each shading system

However, the subdivided windows with exterior motorized louvers produce higher UDI values toward the back of the room compared to the rest of the designs. Tables 6.3 to 6.6 show the UDI values at sensor points grouped by their distance from the west wall. Figures 6.7 to 6.10 demonstrate the distribution of UDI values in the room caused by each shading setup. The low UDI values of the exterior shading at the perimeter area are mainly due to illuminance values exceeding 2000 lux. This is evident in tables 6.7 to 6.10 which show maximum Daylight Autonomy values. DAmax is the fraction of the occupied times during which the illuminance values are above 2000 lux at a sensor. Figures 6.11 to 6.14 display DAmax values in the room for each window configuration.

6.4.2. Daylight Autonomy (DA)

The next daylight metric derived from the hourly illuminance data was daylight autonomy with the threshold of 300 lux. DA(300) at a point represents the percentage of the occupied hours throughout the year when illuminance value is equal or greater than 300 lux. The resultant DA values are presented in tables 6.11 to 6.14. In terms of providing the minimum required light level at desks, the subdivided window with exterior lightshelf and motorized louvers prevails over the rest of the options. The comparison of the DA distributions, illustrated in figures 6.15 to 6.18, indicate that the windows with exterior shading not only provide more daylight in the space, but also distribute it more evenly across the room.

Figure 6.19 shows the average DA in the room with each window design. The superior performance of the exterior shading devices in terms of daylight sufficiency can be explained by the fact that the fixed exterior lightshelves reduce the chance of venetian

Table 6.3: UDI values at the first row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	4%	4%	38%	61%	81%
Existing (Active User)	30%	34%	33%	35%	36%	36%	36%	40%	40%	66%	77%	76%
Exterior Shading	25%	32%	32%	37%	40%	41%	40%	40%	38%	34%	36%	30%
Interior Shading	77%	80%	80%	80%	80%	80%	80%	81%	81%	82%	84%	79%

Table 6.4: UDI values at the second row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North											
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	0%	0%	47%	70%	85%
Existing (Active User)	32%	36%	35%	34%	34%	34%	34%	34%	34%	71%	79%	85%
Exterior Shading	37%	66%	72%	76%	77%	78%	76%	78%	72%	74%	67%	51%
Interior Shading	77%	75%	73%	70%	69%	69%	68%	73%	73%	79%	82%	82%

Table 6.5: UDI values at the third row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North							
	25	**26**	**27**	**28**	**29**	**30**	**31**	**32**
Existing (Passive User)	0%	0%	0%	0%	0%	51%	70%	84%
Existing (Active User)	35%	34%	33%	30%	29%	69%	78%	85%
Exterior Shading	52%	84%	81%	79%	79%	82%	84%	82%
Interior Shading	73%	67%	56%	49%	58%	75%	79%	86%

Table 6.6: UDI values at the forth row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North							
	33	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Existing (Passive User)	0%	0%	0%	0%	0%	51%	72%	85%
Existing (Active User)	32%	32%	28%	23%	22%	66%	77%	85%
Exterior Shading	55%	82%	76%	72%	70%	77%	81%	81%
Interior Shading	71%	60%	38%	24%	32%	70%	78%	85%

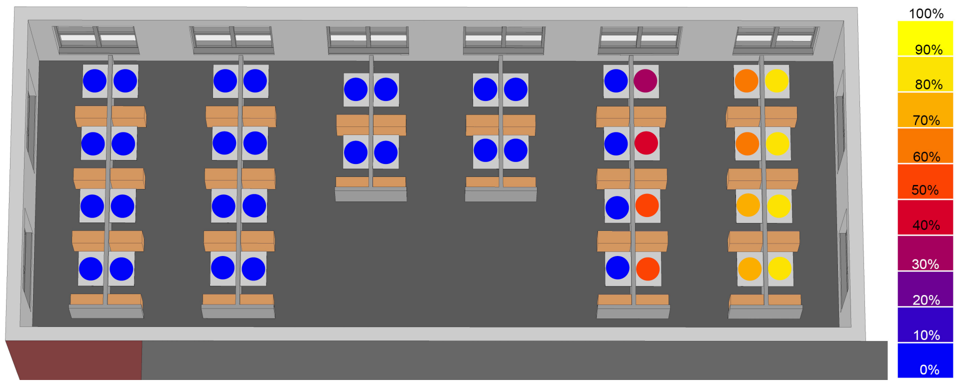


Fig. 6.7: The UDI range on sensor points for existing windows, passive users

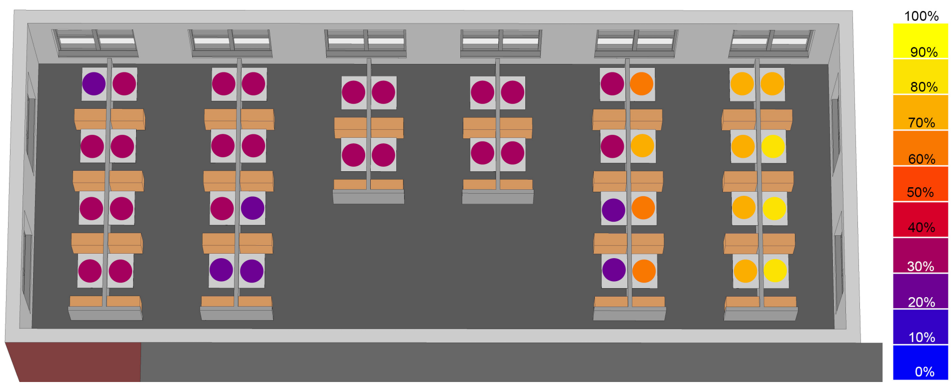


Fig. 6.8: The UDI range on sensor points for existing windows, active users

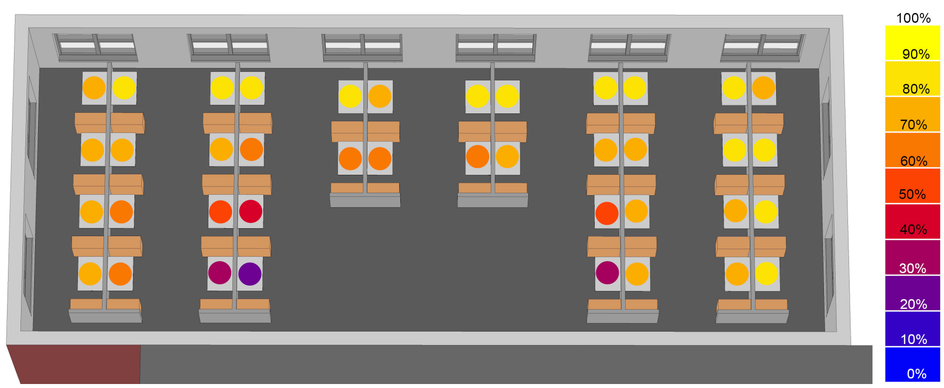


Fig. 6.9: The UDI range on sensor points for subdivided windows with interior shading.

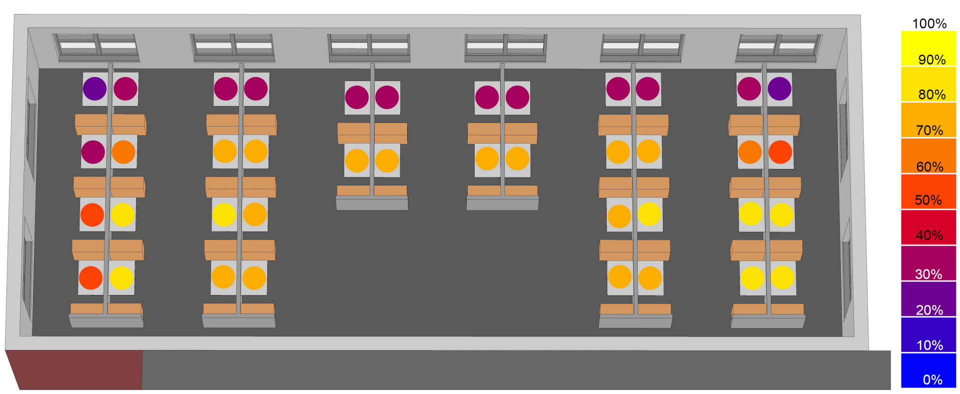


Fig. 6.10: The UDI range on sensor points for subdivided windows with exterior shading.

Table 6.7: DAmax values at the first row of sensors from the west wall

Shading Design	Sensor Number South ←---→ North											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Existing (Active User)	12%	4%	6%	3%	2%	2%	1%	2%	2%	6%	3%	12%
Exterior Shading	70%	61%	61%	55%	51%	51%	51%	52%	54%	59%	57%	65%
Interior Shading	8%	1%	2%	0%	0%	0%	0%	0%	0%	2%	1%	10%

Table 6.8: DAmax values at the second row of sensors from the west wall

Shading Design	Sensor Number South ←---→ North											
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%
Existing (Active User)	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	4%
Exterior Shading	54%	22%	14%	9%	8%	7%	9%	7%	13%	13%	20%	41%
Interior Shading	4%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	7%

Table 6.9: DAmax values at the third row of sensors from the west wall

Shading Design	Sensor Number South ←---→ North							
	25	**26**	**27**	**28**	**29**	**30**	**31**	**32**
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	0%
Existing (Active User)	2%	0%	0%	0%	0%	0%	0%	0%
Exterior Shading	36%	0%	0%	0%	0%	0%	0%	5%
Interior Shading	1%	0%	0%	0%	0%	0%	0%	0%

Table 6.10: DAmax values at the forth row of sensors from the west wall

Shading Design	Sensor Number South ←---→ North							
	33	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	3%
Existing (Active User)	3%	0%	0%	0%	0%	0%	0%	3%
Exterior Shading	33%	0%	0%	0%	0%	0%	0%	8%
Interior Shading	2%	0%	0%	0%	0%	0%	0%	3%

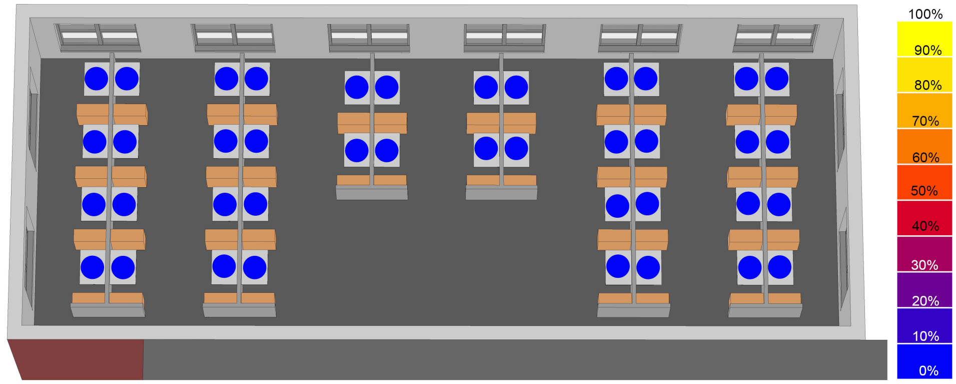


Fig. 6.11: The DAmax range for existing windows, passive users

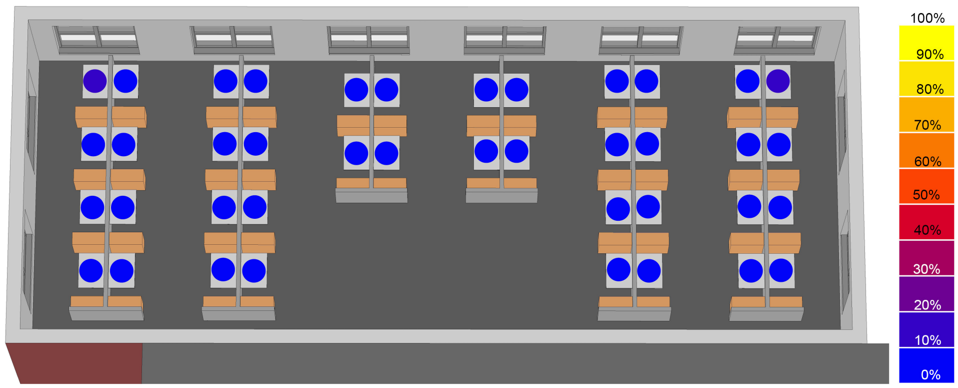


Fig. 6.12: The DAmax range for existing windows, active users

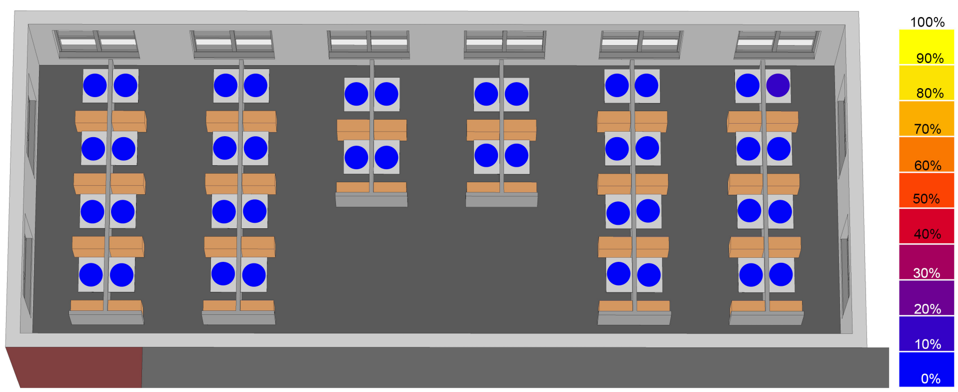


Fig. 6.13: The DAmax range for subdivided windows with interior shading.

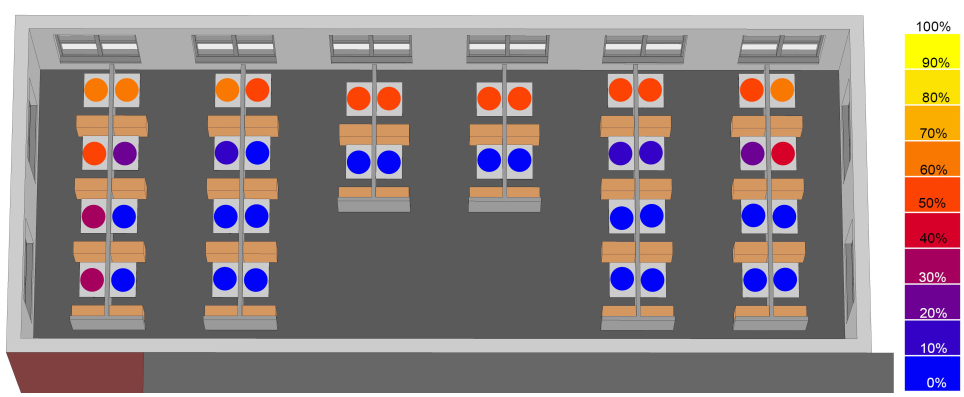


Fig. 6.14: The DAmax range for subdivided windows with exterior shading.

Table 6.11: DA values at the first row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North											
	1	2	3	4	5	6	7	8	9	10	11	12
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	0%	0%	11%	40%	73%
Existing (Active User)	38%	36%	37%	35%	36%	35%	35%	36%	35%	47%	70%	83%
Exterior Shading	92%	90%	91%	89%	89%	88%	88%	89%	89%	91%	90%	92%
Interior Shading	80%	76%	77%	74%	74%	74%	74%	76%	75%	79%	80%	85%

Table 6.12: DA values at the second row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North											
	13	14	15	16	17	18	19	20	21	22	23	24
Existing (Passive User)	0%	0%	0%	0%	0%	0%	0%	0%	0%	15%	55%	83%
Existing (Active User)	37%	34%	33%	31%	31%	30%	30%	31%	31%	48%	73%	85%
Exterior Shading	87%	84%	83%	82%	81%	80%	80%	81%	82%	83%	84%	88%
Interior Shading	74%	66%	58%	53%	51%	51%	51%	58%	58%	73%	76%	85%

Table 6.13: DA values at the third row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North							
	25	26	27	28	29	30	31	32
Existing (Passive User)	0%	0%	0%	0%	0%	18%	55%	79%
Existing (Active User)	33%	30%	28%	23%	22%	46%	69%	81%
Exterior Shading	84%	79%	75%	72%	70%	76%	78%	84%
Interior Shading	64%	46%	36%	25%	29%	64%	72%	82%

Table 6.14: DA values at the forth row of sensors from the west wall

Shading Design	Sensor Number South ←------→ North							
	33	34	35	36	37	38	39	40
Existing (Passive User)	0%	0%	0%	0%	0%	16%	60%	83%
Existing (Active User)	26%	22%	15%	9%	10%	38%	68%	84%
Exterior Shading	83%	75%	68%	61%	59%	68%	75%	85%
Interior Shading	64%	37%	15%	5%	6%	55%	70%	84%

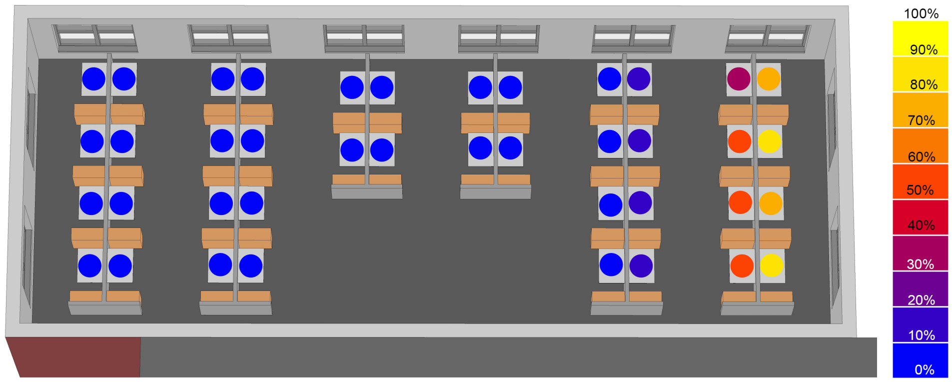


Fig. 6.15: The DA range for existing windows, passive users

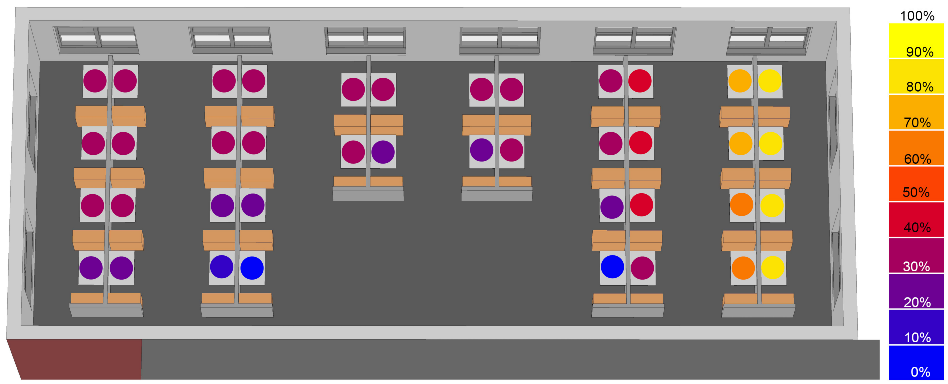


Fig. 6.16: The DA range for existing windows, active users

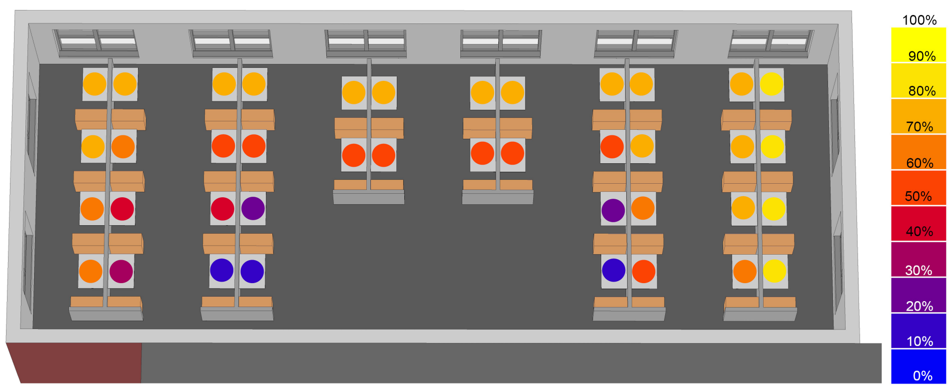


Fig. 6.17: The DA range for subdivided windows with interior shading.

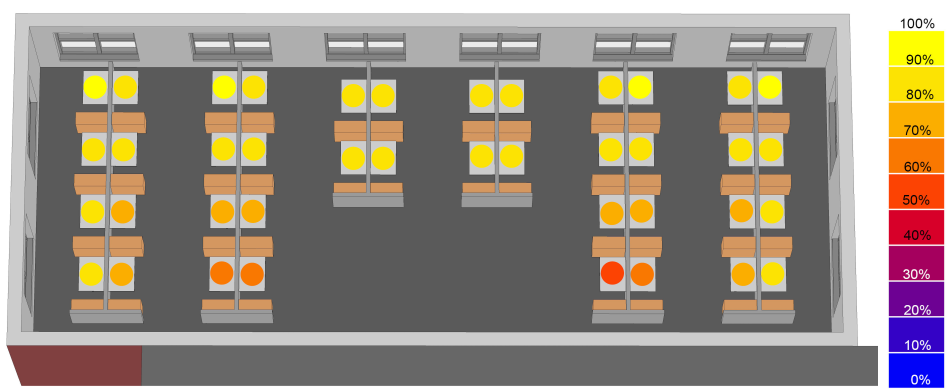


Fig. 6.18: The DA range for subdivided windows with exterior shading.

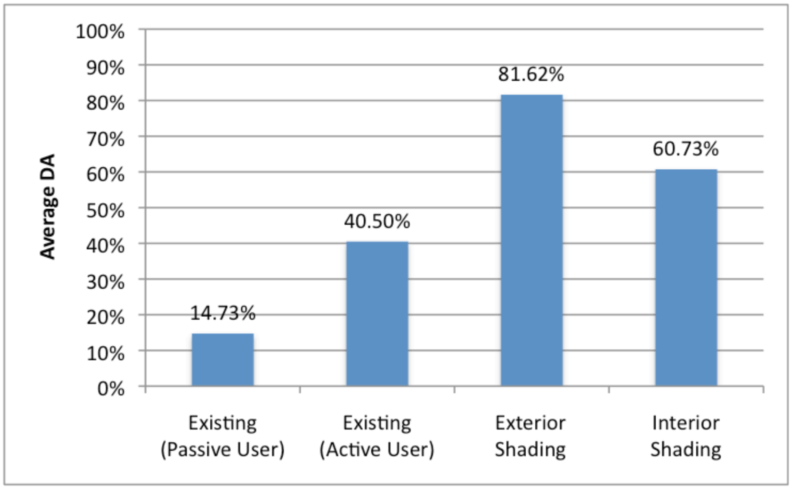


Fig. 6.19: Average DA in the room with each window shading design

blinds being closed. According to the transmitted irradiance data retrieved from Trnsys simulation, the number of hours per year when occupants might close the venetian blinds on west facing windows is 578 with the exterior lightshelf and 1668 without the lightshelf. For the south facing windows the numbers are 1448 and 1990 respectively. Evidently, the lower shade closing incidents result in the higher daylight availability in the room.

6.4.3. Daylight Glare Probability (DGP)

The hourly fish-eye renderings of a viewpoint in the room were analyzed with Evalglare to compute the annual Daylight Glare Probability (DGP) for each window design. Daylight Glare Probability, developed by Wienold and Christofferson (2006), represents "percent of people disturbed". Before calculating the DGP value for each image, Evalglare requires a criterion for determining potential sources of glare. In this study the criterion was set as any part of the image with a luminance value of 2000 cd/m2 or above. After distinguishing the potential sources of glare, Evalglare calculates the DGP value for those areas by entering their size, position, and luminance into the DGP equation below.

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log\left(1 + \sum_{i=1}^{n} \frac{L_{si}^2 \omega_{si}}{E_v^{1.87} P_i^2}\right)$$

A DGP value of 0.35 or higher is considered a disturbing glare condition. The 5-phase method simulation of the 3 shading designs resulted in 14076 rendered images after filtering and consolidation (Figures 6.20 and 6.21). A bash script was created to run Evalglare on all of the images. The resultant DGP values were subsequently processed in a spreadsheet to calculate the annual daylight glare probability for each window shading design. The annual Daylight Glare Probability is simply the percentage of the daylight hours throughout the year when the DGP value is above 0.35. Table 6.15 shows that almost no discomfort glare was detected with any of the shading designs at the studied filed of view.

Table 6.15: Annual DGP calculated for a viewfield in the room

Shading System	**Annual Daylight Glare Probability**
Existing (Passive User)	0%
Existing (Active User)	0%
Exterior Shading	0.06%
Interior Shading	0%

6.5. THERMAL PERFORMANCE OF SHADING DEVICES

One of the advantageous of an exterior shading device over an interior shading device is its ability to control solar heat gain. The interior systems are mainly used for glare control and have minimal effect on solar heat gain. Once the sun rays pass through the glazing and hit the interior objects, they turn into heat with longer wavelength and can not leave the space. A TRNSYS model was developed to compare the annual solar heat gain through the subdivided windows with exterior and interior shading devices. Since TRNSYS is not able to model angled louvers, they were modeled as horizontal slats.

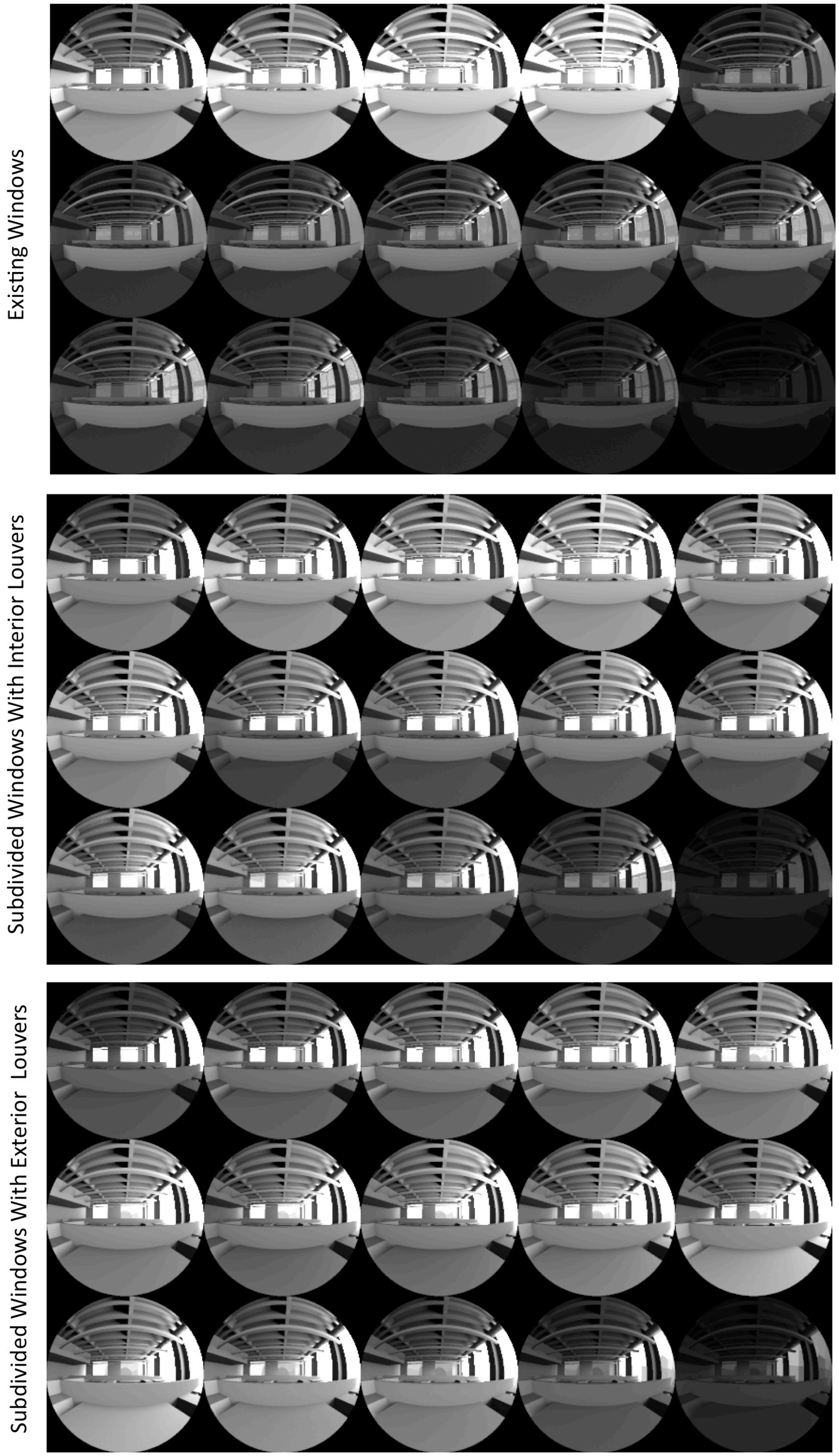


Fig. 6.20: The hourly renderings of the room on summer solstice (6 A.M. to 8 P.M.). The top left image in each group represents 6 AM on Jun 21st, and the lower right image represents 8 PM on the same day.

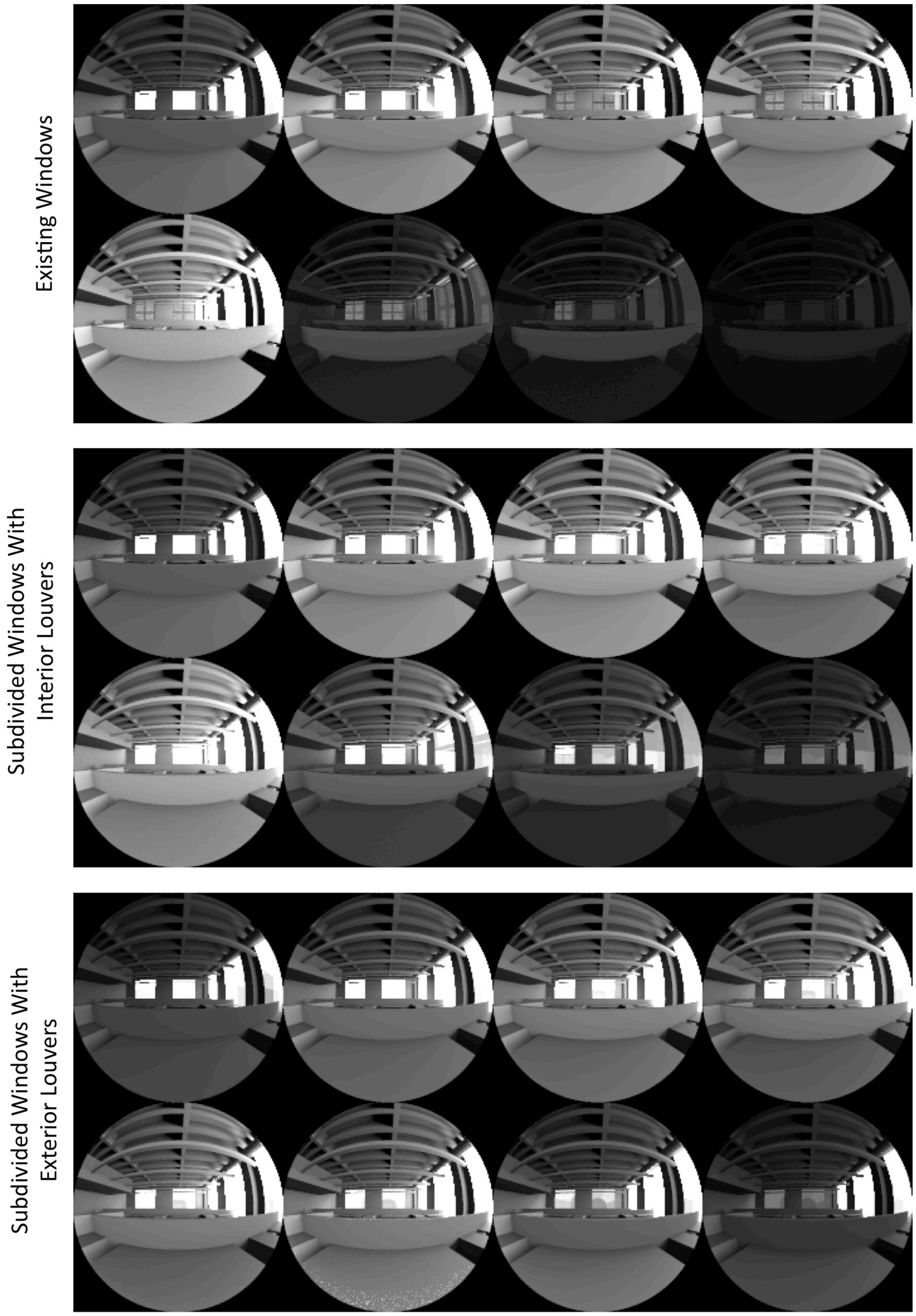


Fig. 6.21: The hourly renderings of the room on winter solstice (9 A.M. to 4 P.M.). The top left image in each group represents 9 AM on Dec 21st, and the lower right image represents 4 PM on the same day.

The resultant Trnsys data of the exterior shading design were sorted with the control algorithm discussed before. Figure 6.22 shows the hourly transmitted solar radiation through both south and west windows with exterior and interior shading. The significantly lower heat gain though exterior shading during the cooling months produces a higher energy saving potential for this system compared to the other two options.

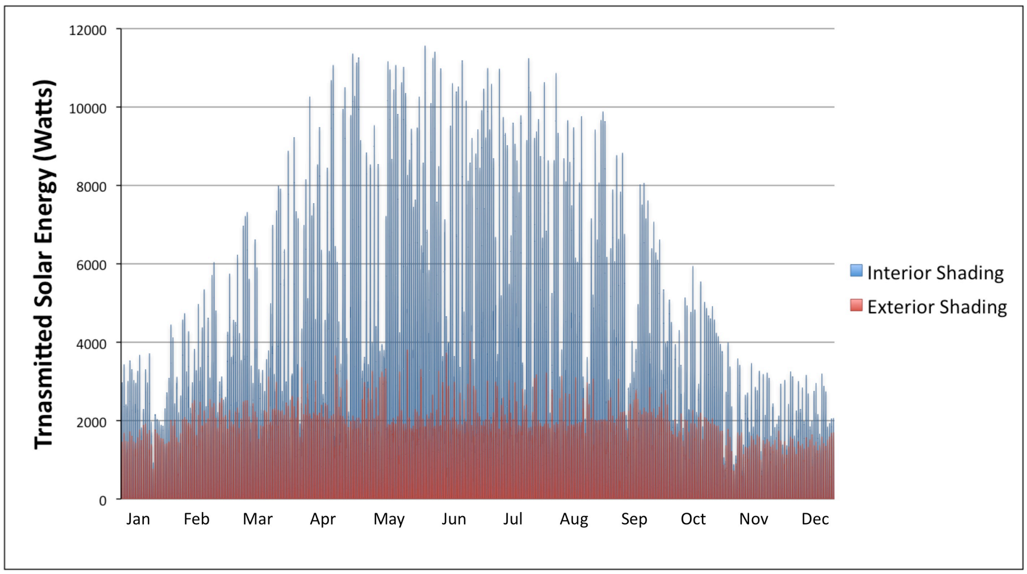


Fig. 6.22: Hourly transmitted solar energy through west and south facing windows

6.6. ELECTRICITY SAVING POTENTIAL

In this section, electricity consumption in the room is estimated for each of the window configurations. The annual electricity usage comprises the annual electric light usage and the shading devices' own electricity use if any.

6.6.1. Calculation of Electric Light Usage

The studied space currently contains 77 two-lamp 32 W fluorescent luminaires. Separate manual switches control the perimeter and core area luminaires. In order to estimate energy saving potential of each window shading design, it was assumed that the luminaires are equipped with photoelectric lighting controls. The core luminaires were

assumed to be turned on when illuminance at sensor 37 (Fig 6.3) was below 300 lux, and the perimeter luminaires would be turned on when illuminance at sensor 19 dropped below 300 lux. The two selected sensors had the lowest DA in their groups. Accordingly, the number of hours when the lights needed to be turned on were calculated and displayed in table 6.16.

Table 6.16: Number of hours during the daytime when electric lights need to be turned on.

Shading System	**Number of hours when illuminance is bellow 300 lux at sensor 19**	**Number of hours when illuminance is bellow 300 lux at sensor 37**
Existing (Passive User)	4686	4686
Existing (Active User)	3290	4229
Exterior Shading	919	1929
Interior Shading	2315	4400

The annual electric light usage in the room was obtained by multiplying table 6.16 values by the power demand of each group of luminaires (Equations 6.1). It can be observed in table 6.17 and figure 6.23 that the subdivided windows with exterior shading devices produce the lowest annual electric light usage, one third of the existing condition. The subdivided windows with interior automatic louvers reveal more than twice electric light usage as the exterior design. It is notable that their performance is relatively close to that of the existing windows with active users, especially in terms of core luminaires' electric light usage.

Equations 6.1: Calculation of the core and perimeter luminaires' power demand

Luminaire specification: 2 lamp T8 32W fluorescent luminaries

Number of luminaries in Perimeter area: 26
Number of luminaries in the core area: 51

Perimeter area lighting energy demand: $26 \times 2 \times 32 = 1664$ *W*

Core area lighting energy demand: $51 \times 2 \times 32 = 3264$ *W*

Table 6.17: Annual electric light usage during daytime

Shading System	Electric light usage at the perimeter area (kWh)	Electric light usage at the core area (kWh)	Total Electric light usage (kWh)
Existing (Passive User)	7797.50	15295.10	23092.61
Existing (Active User)	5474.56	13803.46	19278.02
Exterior Shading	1529.22	6296.26	7825.47
Interior Shading	3852.16	14361.60	18213.76

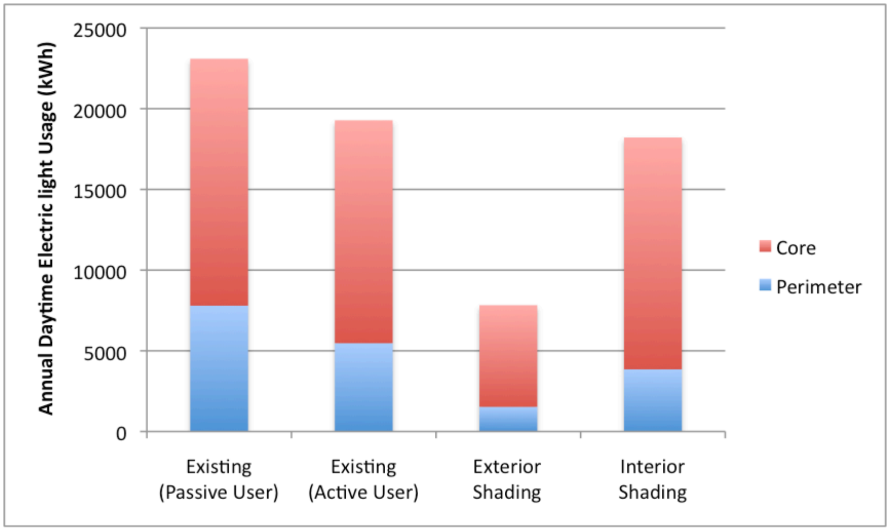


Fig. 6.23: Annual electric light usage in the room with each window design.

6.6.2. The Energy Consumption of Automatic Shading Devices

The energy demand of the motorized louvers were calculated and multiplied by their number of adjustments (Equations 6.2). As a result, the annual electricity consumption of automatic shading devices was found to be about 6 kWh, which is very minimal compared to the electric lights' energy consumption.

6.6.3. Total Electricity Consumption

Table 6.18 shows the total electricity use in the room due to each window design. The subdivided window with exterior louvers and lightshelf still outperforms other options by a huge margin (Figure 6.23). With such system, the annual electricity usage can be reduced to one third compared to the existing situation.

Equations 6.2: Calculation of the automatic shading devices' power demand

Motorized louvers' motor Specification: 110 V AC, 150 Watts, 2in/sec lift speed

The upper window height: 53 inches
The lift duration: 53 / 2 = 26.5 sec
Automatic louvers' energy demand per lift: 150 Watts x 27/3600 h= 1.125 Wh per lift

Number of times when south louvers need to be adjusted: 768
South louvers' annual energy use: 2 x 1.125 x 768 = 1726 Wh

Number of times when west louvers need to be adjusted: 638
West louvers' annual energy use: 6 x 1.125 x 638 = 4306.5 Wh

Automatic louvers' annual energy use: 1726+4306=6032.5 Wh = 6.03 kWh

Table 6.18: Shading designs' total annual energy use

Shading System	**Total Electricity Consumption (kWh)**
Existing (Passive User)	23092.61
Existing (Active User)	19278.02
Exterior Shading	7831.50
Interior Shading	18219.79

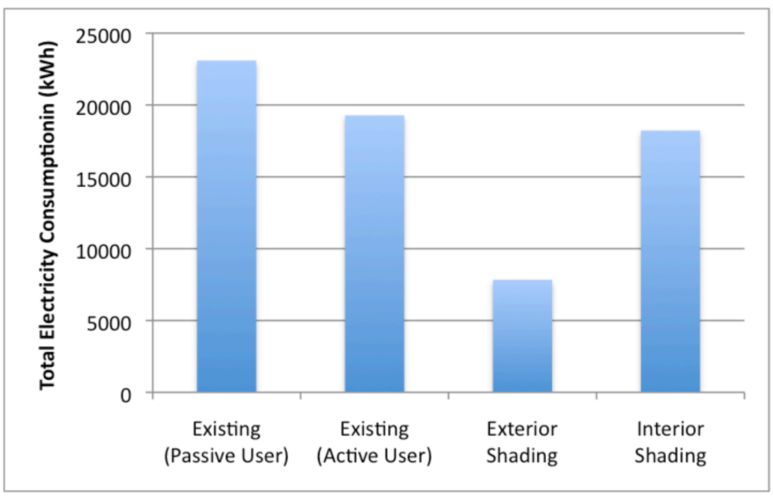


Fig. 6.24: Annual electricity consumption in the room with each window shading design.

6.7. DISCUSSION AND CONCLUSION

This chapter examined daylight performance of three window designs in an existing space. An advanced simulation method was used to perform annual daylight and visual comfort assessment with the consideration of occupants' shade control behavior.

The resulting climate-based (a.k.a. dynamic) daylight metrics showed that a subdivided window consisting of manual venetian blinds on the lower half, an exterior lightshelf in the middle, and an automatically-controlled exterior louver system on the upper half is at least twice more efficient than the subdivided or unsubdivided windows with interior shading devices. The exterior shading devices also revealed a significantly lower solar heat gain through the windows during the cooling months. The additional advantage of an exterior motorized louver over an interior motorized louver is that it will create less noise, as the motor is located outside. However, the exterior shading devices will be exposed to outdoor weather and may require more maintenance compared to the interior solutions.

CHAPTER 7
Conclusions

7.1. CONCLUSIONS

This study aimed at examining the potentials of a subdivided window in solving the current challenges of daylighting side-lit spaces. The first phase of the study, described in chapter 3, looked at the effect of a subdivided window on occupant use of venetian blinds and electric lighting. An open-plan studio space with 40 workstations was selected as the case study. The space was divided into two zones; one containing subdivided windows and the other containing original windows. The subdivided windows featured fixed interior louvers on the upper half and occupant-controlled venetian blinds on the lower half of the windows. The original windows were undivided with venetian blinds installed at the window head. Occupants in the original window zone served as the control group in this study.

The results demonstrated that on average subdivided windows provided 2 hours less electric light usage per day. The survey data did not show a significant difference in occupant satisfaction with their visual environment between the two zones. The window occlusion data in this study suggested that a subdivided window configuration increases occupants' chance of raising the blinds. Given that the environmental conditions such as transmitted vertical irradiance were similar in both groups of windows, occupants' different blind control behavior must have arisen from psychological factors.

The illuminance measurement under overcast sky condition and the review of occupant comments established that a dynamic shading system on the upper part of the subdivided window might further improve its performance. Accordingly, the next phase

of the study focused on the evaluation of various dynamic shading alternatives for the upper part of the subdivided window.

Four design options were simulated using Radiance tools. The design options consisted of subdivided windows with manually controlled venetian blinds on the lower part of the window and the following shading devices on the upper part:

1- Liquid Crystal glass louvers

2- Electrochromic glass louvers

3- Motorized opaque louvers

4- Fixed opaque louvers

Daylight performance and lighting energy saving potential of these systems were evaluated in 5 different climates. Among the studied options, the subdivided window with automated retractable louvers on the upper part proved most efficient in terms of both daylight sufficiency and electricity consumption. The study of the systems in different climates however showed that dynamic shading devices are not justifiable in sunny climates and are suitable for cloudy climates only.

Based on these findings, the subdivided windows in chapter 3 were redesigned with interior and exterior motorized louvers, and the systems' performance was evaluated against the original windows in the studied space. An advanced simulation method was used to perform annual daylight and visual comfort assessment with the consideration of occupants' shade control behavior. The resulting data revealed that a subdivided window consisting of manual venetian blinds on the lower half, an exterior lightshelf in the middle, and an automatically controlled exterior louver system on the upper half has the potential to reduce the lighting energy consumption to one third of the existing condition.

7.2. DISCUSSIONS

When designing with daylight, two different aspects come to play. One is related to optimization of daylight in terms of fenestration size, solar heat gain control, lighting control, etc. The other aspect of daylighting design is to find solutions that facilitate occupant adaptation for maximum comfort. The following sections discuss these two aspects based on the observations in the dissertation.

7.2.1. Daylighting and Architectural Design

Daylighting affects architectural design in numerous levels to the extent that it is difficult to distinguish between daylighting and architectural design. Mt. Angel Abby Library by Alvar Alto provides a perfect example of such consolidation. The structure is truly, in Louis Kahn's terms, a giver of light. Daylight enters the building from various directions and is softly distributed by multiple reflections from the interior surfaces. The main study area in the middle of the building is pleasantly illuminated with daylight pouring down from the skylight as well as daylight coming from the side windows. However, the sources of light are brilliantly hidden from the direct view of the observer, creating a comfortable visual environment (Fig. 7.1).

Alto has applied a specific geometry around the light sources consisting of oblique planes. This geometry yields intermediate surfaces between the windows and their adjacent horizontal or vertical planes. In fact, the oblique surfaces, not only reflect daylight down to the space, but also illuminate the window wall and the surrounding elements (Fig. 7.1). This creates a soft transition from the extremely bright fenestration to the walls and ceilings and reduces the contrast of luminance in the observers' field of view. Accordingly, in Alto's design the goal was not only to illuminate the task, but also

to display the elements of the space. As a result, the electric lights are often turned off in the commons, and the amount of luminaires is minimal compared to the equal size buildings. In many buildings, electric lights need to be turned on only to compensate for the contrast of luminance between different areas.

The space layout is also noteworthy, as it provides various seating areas with different levels of daylight for the visitors to choose from. The bookshelves are located in the area between the core and the perimeter of the building. They are reminiscent of light rays shining from the daylit core toward the rest of the space. Like any other architectural masterpiece, every detail in Alto's design, from the structure to the space layout, seems to have been affected by daylighting.

It is important to note that this delightful daylit environment has been achieved through an optimum area of glazing. It might often be assumed that daylighting requires a sheer amount of glazed area which leads to a significant heat loss in the building. The study of Mt. Angel Abby library shows that by careful positioning and distribution of the windows it is possible to obtain successful natural illumination with a low percentage of heat-wasting glass in the building envelope.

There is a lot to be said about Alto's design. It truly represents a structure that has been fabricated by daylighting from the early stages of its existence. The dynamic nature of daylight makes it one of the most challenging topics in architectural design, however it strongly affects people's perception of a space. Building characteristics such as heavenly, open, mysterious, or gloomy are simply definitions of how daylight enters and travels within a space. In that regard, daylighting must not be seen merely as an energy saving strategy in architecture but the guiding force behind the architectural design.

Fig. 7.1: Mt. Angel Abby library by Alvar Alto. Daylight sources are often hidden from direct view. The oblique surfaces create a soft transition between the light source and the interior surfaces. There are a variety of seating areas with different levels of daylight for the visitors to choose from.

7.2.2. The Behavioral Aspect of Daylighting Design

A successful daylighting design takes into account the adaptive behavior of the occupants. The survey questionnaire revealed valuable data on occupant behavior and attitude toward daylighting. It was designed to understand occupants' view of their visual environment and the logic behind their shade control behavior. As an example, occupants indicated that they mainly closed the manual shades to reduce glare from daylight. Accordingly, a fenestration design without glare control equals no daylight in the space.

However, the shades may remain closed in the absence of glare for a variety of reasons. Based on the survey data, although most participants were interested in raising the shades to admit daylight and maintain visual contact to outside, a number of issues prevented them from doing so. Top in the list was blinds' being inaccessible or hard to adjust. There was also the problem of occupants' concern about others' comfort, especially in the unsubdivided window zone. Accordingly, it is important to provide a shading device that is smooth and accessible in a setting that decreases occupants' fear of exercising their control.

The space layout is another important topic in occupant adaptation. The survey data clearly showed the conflict of interest between the perimeter area occupants and the core area occupants in terms of their daylighting preferences. Perimeter occupants complained about reflections from daylight on their computer screen, heat gain, and glare; while core area occupants were unsatisfied with their lack of view out, lack of control over window blinds, and low daylight due to the lowering of the shades. One simple solution is to place the circulation areas next to windows to reduce the chance of

glare perception by the perimeter area occupants and provide equal access to shading devices for all occupants.

Furthermore, the current contradiction in daylighting design is that computer tasks require low levels of ambient light (150-200 lux), while the recommended light level for occupant well-being is above 1000 lux. This calls for a dynamic work environment where occupants can move from one lighting zone to another based on their task type. Contrary to current office spaces where one spends the entire workday behind a fixed desk, future work environments must be designed to facilitate the movement. Assigned offices or seats may require that people have to contend with glare issues or other concerns (e.g. temperature, noise, etc.) for extended periods of time without an important aspect of choice: the ability to move. This is easily achievable considering the increasing use of mobile devices and cloud computing which eliminate the need for permanent work stations.

7.3. RECOMMENDATIONS FOR FUTURE WORK

This study introduces a number of possible areas for future research, which are outlined below:

1- In this dissertation the effect of a subdivided window on occupants use of blinds and electric lighting was studied in one building on a limited study population. The observational study of occupant light and shading control behavior in spaces equipped with subdivided windows can be repeated in different locations with various shading designs and climates in order to establish a more accurate relationship between the two variables.

2- The current shade control behavioral models have been drawn from correlational studies which monitored the impact of indoor and outdoor environmental conditions on the operation of blinds. This dissertation showed that the window configuration is another influential factor in occupant window blind control behavior. Accordingly, future research could focus on developing a new shade control behavior model which takes into account the effect of the window configuration on occupants use of shading devices.

3- The simulation studies in this dissertation established that subdivided windows which combine automatic and manual shading devices have the potential to significantly reduce the lighting energy use. It is suggested that the annual performance of such systems be evaluated in real buildings in terms of occupant satisfaction, daylight sufficiency, and actual energy savings.

4- The application of the current glare evaluation techniques in Mt. Angel Abby library resulted in a wide range of glare predictions by these methods. This emphasizes the need for a reliable and universal visual comfort assessment method. Establishing such glare evaluation method is another active area of research one may pursue.

BIBLIOGRAPHY

Abdulmohsen, A., Boyer, L. L., & Degelman, L. O. (1994). Evaluation of lightshelf daylighting systems for office buildings in hot climates. *Proceedings of the 9th symposium on improving building systems in hot and humid climates, Arlington, TX*.

Almusaed, A. (2011). Illuminate by light shelves. In: *Biophilic and Bioclimatic Architecture* (pp 325–332). Springer London.

Athienitis A. K., & Tzempelikos, A. (2002). A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device. *Solar Energy*, 72(4), 271-281.

Baetens, R., Jelle, B. P., & Gustavsen, A. (2010). Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. *Solar Energy Materials and Solar Cells, 94(2), 87-105.*

Baker, N., & Steemers, K. (2002). *Daylight design of buildings*. Earthscan/James & James.

Barnes, R. D. (1981). *Perceived freedom and control in the built environment. Cognition, social behavior and the environment*. Hillsdale NJ: Erlbaum.

Bean, A. R., & Hopkins, A. G. (1980). Task and background lighting. *Lighting Research and Technology*, 12(3), 135-139.

Beauchemin, K. M., & Hays, P. (1996). Sunny hospital rooms expedite recovery from severe and refractory depressions. *Journal of Affective Disorders*, 40(1–2), 49–51.

Begemann, S. H. A., Van den Beld, G. J., & Tenner, A. D. (1997). Daylight, artificial light and people in an office environment, overview of visual and biological responses. *International Journal of Industrial Ergonomics*, 20(3), 231-239.

Benedetti, F., Colombo, C., Barbini, B., Campori, E., & Smeraldi, E. (2001). Morning sunlight reduces length of hospitalization in bipolar depression. *Journal of Affective Disorders*, 62(3), 221–223.

Benton, C. C., Warren, M., Selkowitz, S., Verderber, R., McBride, J., Morse, O., & Jewell, J. (1986). *A field evaluation of daylighting system performance*. Center for Environmental Design Research, University of California.

Berson, D. M., Dunn, F. A., & Takao, M. (2002). Phototransduction by retinal ganglion cells that set the circadian clock. *Science*, 295(5557), 1070-1073.

Bordass, B., Cohen, R., Standeven, M., & Leaman, A. (2001). Assessing building performance in use 2: Technical performance of Probe buildings. *Building Research and Information,* 29 (2), 103-113.

Bordass, W., Bromley, K., & Leaman, A. (1993). User and occupant controls in office building. *Proceedings of the Building Design, Technology and Occupant Wellbeing in Temperate Climates Conference*.

Bourgeois, D., Reinhart, C., & Macdonald, I. (2006). Adding advanced behavioural models in whole building energy simulation: A study on the total energy impact of manual and automated lighting control. *Energy and Buildings*, 38(7), 814-823.

Bourgeois, D., Reinhart, C.F., & Ward, G. (2008). Standard daylight coefficient model for dynamic daylighting simulations. *Building Research & Information*, 36(1), 68-82.

Boyce, P. R. (1980). Observations of the manual switching of lighting. *Lighting Research and Technology*, 12(4), 195-205.

Boyce, P. R., Heerwagen, J. H., Jones, C. C., Veitch, J. A., & Newsham, G. R. (2003). *Lighting quality and office work: A field simulation study*. Pacific Northwest National Laboratory.

Boyce, P. R., Veitch, J. A., Newsham, G. R., Jones, C. C., Heerwagen, J., Myer, M., & Hunter, C. M. (2006a). Lighting quality and office work: two field simulation experiments. *Lighting Research and Technology*, 38(3), 191-223.

Boyce, P. R., Veitch, J. A., Newsham, G. R., Jones, C. C., Heerwagen, J., Myer, M., & Hunter, C. M. (2006b). Occupant use of switching and dimming controls in offices. *Lighting Research and Technology*, 38(4), 358-376.

Boyce, P.R. (1981). *Human Factors in Lighting*. London: Applied Science Publishers.

Campbell, D. T., Stanley, J. C., & Gage, N. L. (1963). Experimental and quasi-experimental designs for research (pp. 171-246). Boston: Houghton Mifflin.

Carbonnier, E., Garrison, D., Liu, Y., & Cartwright, V. (2013). Alvar Aalto's Daylight Devices: A Retrospective Daylight Analysis on Mount Angel Abbey library. Proceedings of *PLEA2013: 29th Conference, Sustainable Architecture for a Renewable Future, Munich, Germany*.

Charles, K., & Veitch, J. (2002). *Environmental satisfaction in open-plan environments: 2. Effects of workstation size, partition height and windows*. Report for National Research Council of Canada. Institute for Research in Construction, Ottawa, ON.

Chauvel, P. C. (1982). Glare from windows: current views of the problem. *Lighting Research and Technology*, 14 (1), 31-46.

Clear, R. D., Inkarojrit, V., & Lee, E. S. (2006). Subject responses to electrochromic windows. *Energy and buildings*, 38(7), 758-779.

Cole, R. J., Brown, Z., & McKay, S. (2010). Building human agency: a timely manifesto. *Building Research & Information*, 38(3), 339-350.

Collins, B. L., Fisher, W. S., Gillette, G. L., & Marans, R. W. (1990). Second level post-occupancy evaluation analysis. *Journal of the Illuminating Engineering Society*, 19(2), 21-44.

De Valpine, J. (2013 September 4). Running Radiance on AWS EC2. [Web Log Post]. Retrieved from http://modsimvis.blogspot.com

Edwards, L., & Torcellini, P. A. (2002). *A literature review of the effects of natural light on building occupants*. Golden, CO: National Renewable Energy Laboratory.(No. NREL/TP-550–30769).

Escuyer, S., & Fontoynont, M. (2001). Lighting controls: a field study of office workers' reactions. *Lighting Research and Technology*, 33(2), 77-94.

Farbstein, J., & Kantrowitz, M. (1991). Design Research in the Swamp. In Advances in environment, behavior, and design (pp. 297-318). Springer US.

Fernandes, L. L., Lee, E. S., & Ward, G. (2013). Lighting energy savings potential of split-pane electrochromic windows controlled for daylighting with visual comfort. *Energy and Buildings*. 61 (2013), 8-20.

Finnegan, M. C., & Solomon, L. Z. (1981). Work attitudes in windowed vs. windowless environments. *The Journal of Social Psychology*, 115(2), 291-292.

Floyd, D. B. & Parker, D. S. (1998). Daylighting: *Measuring the Performance of Light Shelves and Occupant-Controlled Blinds on a Dimmed Lighting Systems*. FSECPF-340, Florida Solar Energy Center, Cocoa, FL.

Fontoynont, M. (2002). Perceived performance of daylighting systems: lighting efficacy and agreeableness. *Solar Energy*, 73, (2), 83-94.

Foster, M., & Oreszczyn, T. (2001). Occupant control of passive systems: the use of venetian blinds. *Building and Environment*, 36(2), 149-155.

Freewan, A. A. (2010). Maximizing the lightshelf performance by interaction between lightshelf geometries and a curved ceiling. *Energy Conversion and Management*. 51(8), 1600-1604.

Galasiu, A. D., & Veitch, J. A. (2006). Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Energy and Buildings*, 38(7), 728-742.

Galasiu, A.D., & Reinhart, C.F. (2008). Current daylighting design practice: a survey. *Building Research and Information*, 36(2), 159–174.

Granderson, J., Gaddam, V., DiBartolomeo, D., Li, X., Rubinstein, F., & Das, S. (2010) Field-Measured Performance Evaluation of a Digital Daylighting System. *Leukos* 7(2), 85-101.

Gugliermetti, F., & Bisegna, F. (2005). A model study of light control systems operating with Electrochromic Windows. *Lighting Research and Technology*. 37(1), 3 -20.

Guillemin, A., & Morel, N. (2001). An innovative lighting controller integrated in a self-adaptive building control system. *Energy and Buildings*, 33(5), 477-487.

Halonen, L., & Lehtovaara, J. (1995). *Need of individual control to improve daylight utilization and user's satisfaction in integrated lighting systems*. Publications-Commission Internationale De L Eclairage, CIE,119, 200-203.

Heerwagen, J. H., & Heerwagen, D. R. (1986). Lighting and psychological comfort. *Lighting Design & Application*, 16(4), 47–51.

Heschong Mahone Group. (1999). *Skylight and retail sales: An investigation into the relationship between daylighting and human performance*. Pacific Gas and Electric Company.

Heschong, L. (2002). Daylighting and human performance. *ASHRAE Journal*, 44 (8), 65–67.

Heschong, L. (2003). *Windows and Offices: a Study of Office Worker Performance and the Indoor Environment*. Technical Report. California Energy Commission.

Heschong, L., Howlett, O., McHugh, J., & Pande, A. (2005). Sidelighting Photocontrols Field Study. NEEA and PG&E and SCE. http://www.h-m-g.com/downloads.htm [20, January 2009]

Hopkinson, R.G. (1972). Glare from daylighting in buildings. *Applied Ergonomics*, 3(4), 206–215.

Hopkinson, R.G. & Bradley, R.C. (1960). A study of glare from very large sources. *Illuminating Engineering*, 55(5), 288–294.

Hua, Y., Oswald, A., & Yang, X. (2011). Effectiveness of daylighting design and occupant visual satisfaction in a LEED Gold laboratory building. *Building and Environment*, 46(1), 54-64.

Hunt, D. R. G. (1979). The use of artificial lighting in relation to daylight levels and occupancy. *Building and Environment*, 14(1), 21-33.

Inanici, M. N. (2006). Evaluation of high dynamic range photography as a luminance data acquisition system. *Lighting Research and Technology*, 38(2), 123-134.

Inkarojrit, V. (2005). *Balancing comfort: Occupants' control of window blinds in private offices* (Doctoral dissertation, University of California, Berkeley).

International Commission on Illumination (CIE) (1983). *Discomfort glare in the interior working environment*. CIE Publication 55.

International Commission on Illumination (CIE) (1995). *Discomfort glare in interior lighting*. CIE Publication 117.

International Commission on Illumination (CIE) (2002). *Glare from small, large and complex sources*. CIE Publication 147.

Iwata, T., Shukuja, M., Somekawa, N., & Kimura, K. (1992). Experimental study on discomfort glare caused by windows. *Journal of Architectural Planning and Environmental Engineering*, Part 1: Subjective response to glare from a simulated window, 432, 21–33; Part 2: Subjective response to glare from actual windows, 439, 19–33.

Iwata, T., Somekawa, N., Tokura, M., Shukuya, M., & Kimura, K. (1991). Subjective response on discomfort glare caused by windows. The 22nd Session of the CIE-Division 3. Melbourne, Australia.

Jain, P. (1998). *Occupant response to the automatic interior shading system at the new main San Francisco Public Library*. M.S. Thesis. University of California, Berkeley: 339.

Jakubiec, A., & Reinhart, C. (2010). The use of glare metrics in the design of daylit spaces: Recommendations for practice. *In 9th International Radiance Workshop in Freiburg, Germany, September 2010*.

Jakubiec, A., & Reinhart, C. (2012). The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces. *Lighting Research and Technology*, 44 (2), 149-170

Jennings, J. D., Rubinstein, F. M., DiBartolomeo, D., & Blanc, S. L. (2000). Comparison of control options in private offices in an advanced lighting controls testbed. *Journal of Illuminating Engineering Society*, 29(2), 39-60.

Karlsson, J. (2001). Control system and energy savings potential for switchable windows. *7th International IBPSA Conference, Rio de Janeiro, Brazil*.

Kim, J. T., Shin, H. Y., & Kim, G. (2005). Comparative Evaluation of Sloped Lightshelf using Scale Model Measurements. In Proceedings of *JSES/JWEA Joint Conference. 515-518*.

Kim, Y., Lim, J., Hong, S., Kwun J., Choi, A., ,& Kim Y.S. (2010). Luminous Characteristics of Shading Materials for Office Buildings: Perforated Panels vs.Fabric Blinds. *Leukos*, 6(3), 227-240.

Klems, J.H., 1994a. A new method for predicting the solar heat gain of complex fenestration systems: I. Overview and derivation of the matrix layer calculation, *ASHRAE Transactions* 100 (1): 1065-1072.

Klems, J.H., 1994b. A new method for predicting the solar heat gain of complex fenestration systems: II. Detailed description of the matrix layer calculation, *ASHRAE Transactions* 100 (1): 1073-1086.

Konis, K. S. (2012). *Effective Daylighting: Evaluating Daylighting Performance in the San Francisco Federal Building from the Perspective of Building Occupants* (Doctoral dissertation, University of California, Berkeley).

Kroner, W. M., Stark-Martin, J. A., & Willemain, T. (1992). *Rensselaer's West Bend Mutual Study: using advanced office technology to increase productivity*. Center for Architectural Research, Rensselaer.

Kurian, C.P., Aithal, R., S., Bhat, J., & George, V.I. (2008). Robust control and optimization of energy consumption in daylight–artificial light integrated schemes. *Lighting Research and Technology*, 40, 7–24.

LBNL. City of Berkeley (14 Person Office), http://eetd.lbl.gov/BTD/lsr/ld_table_case2.html. participant surveys, http://eetd.lbl.gov/BTD/lsr/ld_table_case9.html. Last accessed Nov. 2004.

Leather, P., Pyrgas, M., Beale, D., & Lawrence, C. (1998). Windows in the Workplace Sunlight, View, and Occupational Stress. *Environment and Behavior*, 30(6), 739-762.

Lee, E. S., & Selkowitz, S. E. (1994). *The design and evaluation of integrated envelope and lighting control strategies for commercial buildings*. (No. LBNL-34638; CONF-950104-3). Lawrence Berkeley Lab., CA (United States).

Lee, E. S., DiBartolomeo, D. L., & Selkowitz, S. E. (1998). Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office. *Energy and buildings*, 29(1), 47-63.

Lee, E. S., DiBartolomeo, D. L., Vine, E.L., & Selkowitz, S. E. (1998). Integrated performance of an automated venetian blind/electric lighting system in a full-scale private office. Proceedings of *the ASHRAE/DOE/BTECC Conference: Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater Beach, Florida*.

Lee, E. S., Fernandes, L. L., Coffey, B., McNeil, A., & Clear, R. (2013). *A Post-Occupancy Monitored Evaluation of the Dimmable Lighting, Automated Shading, and Underfloor Air Distribution System in The New York Times Building*. (LBNL-6023E). Lawrence Berkeley Lab., CA (United States).

Lee, S. Y., & Brand, J. L. (2005). Effects of control over office workspace on perceptions of the work environment and work outcomes. *Journal of Environmental Psychology*, 25(3), 323-333.

Li, D. H., Lam, T. N., & Wong, S. L. (2006). Lighting and energy performance for an office using high frequency dimming controls. *Energy Conversion and Management,* 47(9), 1133-1145.

Lindelöf, D., & Morel, N. (2006). A field investigation of the intermediate light switching by users. *Energy and buildings*, 38(7), 790-801.

Linsay, C. R. T., & Littlefair, P. J. (1993). *Occupant use of venetian blinds in offices*. Watford: Building Research Establishment.

Littlefair, P. J. (1995). Light shelves: computer assessment of daylighting performance. *Lighting Research and Technology*. 27(2), 79–91.

Littlefair, P. J., & Motin, A. (2001). Lighting controls in areas with innovative daylighting systems: a study of sensor type. *Lighting Research and Technology*, 33(1), 59-73.

Love, J. A. (1995). Field performance of daylighting systems with photoelectric controls. *In 3rd European Conference on Energy-Efficient Lighting, Newcastle-upon-Tyne, UK*.

Love, J. A. (1998). Manual switching patterns in private offices. *Lighting Research and Technology*, 30(1), 45-50.

Mahdavi, A., Mohammadi, A., Kabir, E., & Lambeva, L. (2008). Occupants' operation of lighting and shading systems in office buildings. *Journal of Building Performance Simulation,* 1(1): 57-65.

Mahone, D. (1989). Hugh building prototype for large-scale daylighting design. *Architectural Lighting*, 3(4), 23-26.

Maniccia, D., Rutledge, B., Rea, M. S., & Morrow, W. (1999). Occupant use of manual lighting controls in private offices. *Journal of the Illuminating Engineering Society*, 28(2), 42-56.

McHugh, J., Pande A., Ander, G., & Melnyk, J. (2004). Effectiveness of Photocontrols with Skylighting. *IESNA Annual Conference Proceedings*.

McKennan, G. T., & Parry, C. M. (1984). An investigation of task lighting for offices. *Lighting Research and Technology*, 16(4), 171-186.

McNeil, A. (2013a). The Three-Phase Method for Simulating Complex Fenestration with Radiance. LBNL. Available at: http://www.radiance-online.org/learning/tutorials/Tutorial-ThreePhaseMethod.pdf

McNeil, A. (2013b). The Five-Phase Method for Simulating Complex Fenestration with Radiance. LBNL. Available at: http://www.radiance-online.org/learning/tutorials/fivephasetutorialfiles/Tutorial-FivePhaseMethod_v2.pdf

McNeil, A., & Lee, E. S. (2013). A validation of the Radiance three-phase simulation method for modeling annual daylight performance of optically complex fenestration systems. *Journal of Building Performance Simulation*, 6(1), 24-37.

Miller, N. (1998). A recipe for lighting quality. *The First CIE Symposium on Lighting Quality*. *Ottawa, Canada*.

Mistrick, R., & Sarkar, A. (2005). A study of daylight-responsive photosensor control in five daylighted classrooms. *Journal of the Illuminating Engineering Society*, 1(3), 51-74.

Moeck, M., Lee, E.S., Rubin, M., Sullivan, R., & Selkowitz, S. (1998). Visual quality assessment of electrochromic and conventional glazings. *Solar Energy Materials and Solar cells*, 54, 157-164.

Molinelli, J. F. & Boyer, L. L. (1987). Measurements and comparisons of lightshelf performance in two Texas office buildings. Proceedings of *the 5th Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*. *Houston, TX*.

Moore, T., Carter, D. J., & Slater, A. I. (2002a). A field study of occupant controlled lighting in offices. *Lighting Research and Technology*, 34(3), 191-202.

Moore, T., Carter, D. J., & Slater, A. I. (2002b). User attitudes toward occupant controlled office lighting. *Lighting Research and Technology*, 34(3), 207-216.

Moore, T., Carter, D. J., & Slater, A. I. (2003a). A qualitative study of occupant controlled office lighting. *Lighting Research and Technology*, 35(4), 297-314.

Moore, T., Carter, D. J., & Slater, A. I. (2003b). Long-term patterns of use of occupant controlled office lighting. *Lighting Research and Technology*, 35(1), 43-57.

Nazzal, A. A. (2005). A new evaluation method for daylight discomfort glare. *International Journal of Industrial Ergonomics* , 35, 295-306.

Ne'eman, E. (1984). A comprehensive approach to the integration of daylight and electric light in buildings. *Energy and buildings*, 6(2), 97-108.

Newsham, G. R., Aries, M. B. C., Mancini, S., & Faye, G. (2008). Individual control of electric lighting in a daylit space. *Lighting Research and Technology*, 40(1), 25-41.

Newsham, G. R., Mancini, S., & Marchand, R. G. (2008). Detection and Acceptance of Demand Responsive Lighting in Offices with and without Daylight. *Leukos,* 4(3), 139-156.

Newsham, G., Arsenault, C., Veitch, J., Tosco, A. M., & Duval, C. (2005). Task lighting effects on office worker satisfaction and performance, and energy efficiency. *Leukos*, 1(4), 7-26.

Newsham, G., Brand, J., Donnelly, C., Veitch, J., Aries, M., & Charles, K. (2009). Linking indoor environment conditions to job satisfaction: a field study. *Building Research & Information*, 37(2), 129-147.

Newsham, G., Veitch, J., Arsenault, C., & Duval, C. (2004). *Effect of dimming control on office worker satisfaction and performance*. Institute for Research in Construction, National Research Council, Canada.

Nicol, F., Wilson, M., & Chiancarella, C. (2006). Using field measurements of desktop illuminance in European offices to investigate its dependence on outdoor conditions and its effect on occupant satisfaction, and the use of lights and blinds. *Energy and buildings,* 38(7), 802-813.

Ochoa, C. E. & Capeluto, I. G. (2006). Evaluating visual comfort and performance of three natural lighting systems for deep office buildings in highly luminous climates. *Building and Environment*. 41(8), 1128-1135.

Osterhaus, W. K. (2001). Discomfort glare from daylight in computer offices: how much do we really know? Proceedings of *LUX Europa*, 448-456.

Osterhaus, W. K. (2005). Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy* , 79, 140-158.

Papaefthimiou, S., Syrrakou, E., Yianoulis, P. (2006). Energy performance assessment of an electrochromic window. *Thin Solid Films*, 502, 257 – 264.

Park, C., Augenbore, G., & Messadi, T. (2003). Daylighting optimization in smart façade systems. *8th Intenational IBPSA Conference. Eindhoven, Netherlands.*

Pauley, S. M. (2004). Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue. *Medical Hypotheses*, *63*(4), 588-596.

Perez, R., Seals, R., & Michalsky, J. (1993). All-weather model for sky luminance distribution-preliminary configuration and validation. *Solar energy*, 50(3), 235-245.

Rea, M. (1984). Window blind occlusion: a pilot study. *Building and Environment*, 19(2), 133-137.

Rea, M. S. (1983). Behavioral responses to a flexible desk luminaire. *Journal of the Illuminating Engineering Society*, 13(1), 174-190.

Rea, M. S. (2000). *The IESNA lighting handbook: reference & application.*

Reinhart C. F., & Fitz, A. (2006). Findings from a survey on the current use of daylight simulations in building design. *Energy and Buildings*, 38, 824–835.

Reinhart, C. F. (2004). Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. *Solar Energy*, 77(1), 15-28.

Reinhart, C. F. (2006). *Tutorial on the use of daysim simulations for sustainable design.* Retrived from Institute for Research in Construction, National Research Council Canada: http://www.nrc-cnrc.gc.ca/eng/projects/irc/daysim.html

Reinhart, C. F., & Selkowitz, S. E. (2006). Guest editorial: Daylighting–light, form, and people. *Energy and Buildings*, 38(7), 715-717.

Reinhart, C. F., & Voss, K. (2003). Monitoring manual control of electric lighting and blinds. *Lighting Research and Technology*, 35(3), 243-258.

Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *Leukos,* 3(1), 7-31.

Robbins, C. L. (1986). *Daylighting: Design and analysis*. New York: Van Nostrand Reinhold.

Roche, L. (2002). Summertime performance of an automated lighting and blinds control system. *Lighting Research and Technology*, 34(1), 11-27.

Romm, J. J., & Browning, W. D. (1994). *Greening the building and the bottom line: Increasing productivity through energy-efficient design*. Rocky Mountain Institute.

Roulet, C. A., Johner, N., Foradini, F., Bluyssen, P., Cox, C., Fernandes, E. D. O., ... & Aizlewood, C. (2006). Perceived health and comfort in relation to energy use and building characteristics. *Building research and information*, 34(5), 467-474.

Rubin, A. I., Collins, B.L. & Tibbott, R.L. (1978). *Window blinds as a potential energy saver - A case study* (NBS Building Science Series 112). Washington, DC: U.S. Department of Commerce, National Bureau of Standards.

Rubinstein, F. & Enscoe A. (2010). Saving Energy with Highly-Controlled Lighting in an Open-Plan Office. *Leukos*, 7(1), 21-36.

Rubinstein, F., Jennings, J., Avery, D., & Blane, S. (1999). Preliminary results from an advanced lighting controls testbed. *Journal of the Illuminating Engineering Society*, 28(1), 130-141.

Sarkar, A., & Mistrick, R. G. (2006). A novel lighting control system integrating high dynamic range imaging and DALI. *Journal of the Illuminating Engineering Society*, 2(4), 307-322.

Schiler, M. E., & Shweta, J. A. (1997). *Interior Illuminance, Daylight Controls, and Occupant Response*. Retrieved from Vital Signs Curriculum Materail Project: http://arch.ced.berkeley.edu/vitalsigns/res/rps.html

Selkowitz, S.E., Rubin, M., Lee, E.S., Sullivan, R., Finlayson, & E., Hopkins, D. (1994) A review of electrochromic window performance factors. Proceedings of SPIE*: International symposium on optical materials technology for energy efficiency and solar energy conversion XIII. Freiburg, Germany*.

Simpson, M. D. (1990, April). A flexible approach to lighting design. *Proceedings of the CIBSE National Lighting Conference Cambridge, England 8 (pp. 182-189)*.

Stevens, S. (2001). Intelligent façades: Occupant control and satisfaction. *International Journal of Solar Energy*, 21, 147-160.

Sullivan, R., Rubin, M., & Selkowitz, S. (1997). Energy performance analysis of prototype electrochromic windows. *American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) annual meeting*. *Boston, MA*.

Sutter, Y., Dumortier, D., & Fontoynont, M. (2006). The use of shading systems in VDU task offices: A pilot study. *Energy and Buildings*, 38(7), 780-789.

Tabuchi, Y., Matsushima, K., & Nakamura, H. (1995). Preferred Illuminances on Surrounding Surfaces in Relation to Task Illuminance in Office Room Using Task-ambient Lighting. *Journal of Light & Visual Environment*, 19(1), 28-39.

Tiller, D. K., Pasini, I. C., Jaekel, R. R., Newsham, G. R., & Iwata, T. (1995). Furniture mounted lighting system performance: 1. lighting energy consumption. *The CIE 23rd Session, New Delhi, India*.

To, D. W. T., Sing, L. K., Chung, T. M., & Leung, C. S. (2002). Potential energy saving for a side-lit room using daylight-linked fluorescent lamp installations. *Lighting Research and Technology,* 34(2), 121-132.

Tregenza, P.R., 1983. Daylight coefficients. *Lighting Research and Technology*, 15(2), 65-71.

Tzempelikos, A., & Athienitis, A. K. (2007). The impact of shading design and control on building cooling and lighting demand. *Solar Energy*, 81(3), 369-382.

U.S. Green Building Council (2009). *LEED 2009 for New Construction and Major Renovations*. *Reference guide*.

Van Den Wymelenberg, K., & Inanici, M. (2009). A Study of Luminance Distribution Patterns and Occupant Preference in Daylit Offices. Proceedings of PLEA2009: *26th Conference on Passive and Low Energy Architecture*. *Quebec City, Canada*.

Van Den Wymelenberg, K., Inanici, M., & Johnson, P. (2010). The effect of luminance distribution patterns on occupant preference in a daylit office environment. *Leukos*, 7(2), 103-122.

Vartiainen, E., Peippo, K., & Lund, P. (1999). Daylight optimization of multifunctional solar facades. *Solar Energy*, 68, 223.

Veitch, J. A. (1990). Office noise and illumination effects on reading comprehension. *Journal of Environmental Psychology*, 10(3), 209-217.

Veitch, J. A. (2000). Creating high-quality workplaces using lighting. Clements-Croome, D. (Hrsg. 2000*): Creating the Productive Workplace*, London und New York, 207-224.

Veitch, J. A. (2001). Psychological processes influencing lighting quality. *Journal of the Illuminating Engineering Society*, 30(1), 124-140.

Veitch, J. A., & Gifford, R. (1996a). Choice, perceived control, and performance decrements in the physical environment. *Journal of Environmental Psychology*, 16(3), 269-276.

Veitch, J. A., & Gifford, R. (1996b). Assessing beliefs about lighting effects on health, performance, mood, and social behavior. *Environment and Behavior*, 28(4), 446-470.

Veitch, J. A., & Newsham, G. R. (2000a). Exercised control, lighting choices, and energy use: An office simulation experiment. *Journal of Environmental Psychology, 20(3), 219-237*.

Veitch, J. A., & Newsham, G. R. (2000b). Preferred luminous conditions in open-plan offices: Research and practice recommendations. *Lighting Research and Technology*, 32(4), 199-212.

Veitch, J. A., & Newsham, G. R., (1995). Quantifying lighting quality based on experimental investigations of end user performance and preference. Proceedings of Right Light Three: *The Third European Conference on Energy-Efficient Lighting*. *Newcastle-upon-Tyne, England*.

Veitch, J. A., Charles, K. E., Farley, K. M., & Newsham, G. R. (2007). A model of satisfaction with open-plan office conditions: COPE field findings. *Journal of Environmental Psychology*, 27(3), 177-189.

Veitch, J. A., Newsham, G. R., Boyce, P. R., & Jones, C. C. (2008). Lighting appraisal, well-being and performance in open-plan offices: A linked mechanisms approach. *Lighting Research and Technology*, 40(2), 133-151.

Velds, M. (2002). User acceptance studies to evaluate discomfort glare in daylit rooms. *Solar Energy*, 73(2), 95-103.

Vine, E., Lee, E., Clear, R., DiBartolomeo, D., & Selkowitz, S. (1998). Office worker response to an automated venetian blind and electric lighting system: a pilot study. *Energy and Buildings*, 28(2), 205-218.

Vischer, J. C. (2007). The effects of the physical environment on job performance: towards a theoretical model of workspace stress. *Stress and Health*, 23(3), 175-184.

Ward, L. G. & Shakespeare, R., (1998). *Rendering with Radiance: The Art and Science of Lighting Visualization*. San Francisco: Morgan Kaufmann.

Ward, G., Mistrick, R., Lee, E. S., McNeil, A., & Jonsson, J., (2011). Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance. *Leukos* 7(4), 241-261.

Waters, C., Mistrick, R. G., & Bernecker, C. A. (1995). Discomfort glare from sources of non-uniform luminance. *Journal of the Illuminating Engineering Society*, 24 (2), 73–85.

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38, 743–757.

Williams, A., Atkinson, B., Garbesi, K., Rubinstein, F., & Page, E. (2011). *A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings* (No. LBNL-5095E). Lawrence Berkeley National Laboratory, Berkeley, CA (US).

Wilson, S., & Hedge, A. (1987). *The office environment survey: a study of building sickness*. Building Use Studies Ltd, London.

Windows for High Performance Commercial Buildings. (n.d.) Retrieved January 6, 2014 from http://www.commercialwindows.org

Wyon, D. P. (2000). Individual control at each workplace: the means and the potential benefits. In: *Creating the productive workplace*, 192-206.

Yoshida-Hunter, M. (2003). *The influence of type of lighting and visual task on dimming*. MSc Thesis, Troy, NY: Rensselaer Polytechnic Institute.

APPENDIX A: Occupant Satisfaction Survey Questionnaire

University of Wisconsin - Milwaukee

IRB Number: 12.251

IRB Approval date: 2/17/2012

Occupant Satisfaction Survey
Study title: Occupant impact on Lighting Energy Use in Work Environments
Contact: Leyla Sanati (lsanati@uwm.edu)

1- In the table below, please indicate your typical usage hours of the studio.

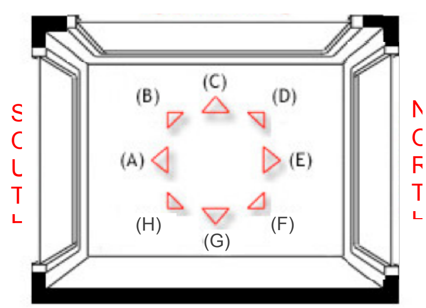
	12 a.m.	1	2	3	4	5	6	7	8	9	10	11	12 p.m.	1	2	3	4	5	6	7	8	9	10	11
S																								
M																								
T																								
W																								
R																								
F																								
S																								

2- When working at your desk what percentage of your time is spent on the following tasks?

Working with computer __________%
Sketching/Reading __________%
Discussion __________%
Other __________%

3- What is your relationship with windows while looking at your computer screen?

- ☐ A
- ☐ B
- ☐ C
- ☐ D
- ☐ E
- ☐ F
- ☐ G
- ☐ H



4- How far are you located from the North wall?

- ☐ 3 - 6 feet
- ☐ 6 - 30 feet
- ☐ 30 - 60 feet
- ☐ More than 60 feet

5- How far are you located from the West wall?

- ☐ 3 - 6 feet
- ☐ 6 - 20 feet
- ☐ More than 20 feet

6- How satisfied are you with the following factors:

	Very Satisfied			Neutral			Very dissatisfied
Amount of electric light in this space	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Amount of daylight in this space	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Distribution of daylight in the space	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Distribution of electric light in the space	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Amount of light for computer tasks	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Amount of light for paper-based tasks	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Amount of control you have over electric lighting	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Amount of control you have over daylight	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
The access to view out	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Visual comfort (dissatisfaction means problems with glare, reflections, contrast)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

Comments ………………………………………………………………………………………

7- How do you evaluate the thermal condition of your environment?

	Very Cold			Neutral			Very Hot
Thermal comfort	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

8- **Which of the following factor(s) contribute(s) to your dissatisfaction with the visual environment in this studio**?

- ☐ Too dark even with electric lights on
- ☐ Too bright even with the lights off
- ☐ Too much daylight
- ☐ Not enough daylight
- ☐ Too much electric lighting
- ☐ Not enough electric lighting
- ☐ Too dark for paper-based tasks
- ☐ Too bright for computer-based tasks
- ☐ Overhead lights not where I need it
- ☐ Task light not adequate or flexible
- ☐ Electric lighting has undesirable color
- ☐ Reflections from daylight on computer screen
- ☐ Reflections from electric light on computer screens
- ☐ Glare from windows
- ☐ Shadows on the work surface
- ☐ Blinds hard to operate
- ☐ Not enough view out
- ☐ Other (please specify) ---

9- How often do you experience the following condition in this studio?

	Always	Daily Mornings	Daily Afternoons	Occasionally	Never
Too much daylight	[ ]	[ ]	[ ]	[ ]	[ ]
Not enough daylight	[ ]	[ ]	[ ]	[ ]	[ ]
Too dark for paper-based tasks	[ ]	[ ]	[ ]	[ ]	[ ]
Too bright for computer-based tasks	[ ]	[ ]	[ ]	[ ]	[ ]
Reflections from daylight on computer screens	[ ]	[ ]	[ ]	[ ]	[ ]
Glare from windows	[ ]	[ ]	[ ]	[ ]	[ ]
Shadows on the work surface	[ ]	[ ]	[ ]	[ ]	[ ]
Not enogh view out	[ ]	[ ]	[ ]	[ ]	[ ]

10- How often do you adjust the venetian blinds in the studio?

- ☐ I rarely adjust the blinds
- ☐ Once per week
- ☐ Once per day
- ☐ 2-3 times per day
- ☐ Other. Please specify…………………………

11- Are there any particular time of day when you close the window blinds located near your workstation?

- ☐ The blinds are closed all day long
- ☐ During the morning
- ☐ During the afternoon
- ☐ The blinds are open all day long
- ☐ Other. Please specify ………………………………

12- What are the primary reasons for lowering/closing the venetian blinds?

- ☐ To reduce glare/brightness from daylight
- ☐ To reduce the heat from the sun
- ☐ To eliminate the reflections on my computer screen
- ☐ To decrease the visual stimulus from outside
- ☐ Other. Please specify ………………………..

13- What are the primary reasons for raisng/opennig the venetian blinds?

- ☐ To increase the level of daylight in the studio
- ☐ To increase the daylight level on my desk
- ☐ To feel the warmth of the sun
- ☐ To maintain visual contact to the outside
- ☐ To increase room spaciousness
- ☐ Other. Please specify …………………………

14- What are the primary reasons for NOT raising/opening the venetian blinds when disturbing factors are eliminated?

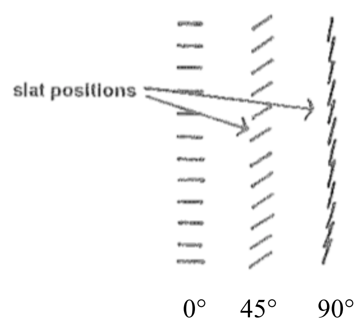
- ☐ The blind control is not easy to access
- ☐ The blind control is hard to operate
- ☐ I am too busy too adjust the blinds routinely
- ☐ I don't want to disturb the class
- ☐ I try to avoid complains from other students
- ☐ Other. Please specify ……………………………………

15- When you close/open the venetian blinds, what is the approximate position of the shades?

- ☐ Blind is either fully raised or fully closed
- ☐ Blind covers 50% of the window area
- ☐ Blind covers 75% of the window area
- ☐ Blind covers 25% of the window area

16- What is the approximate slats angle when you lower the venetian blinds?

- ☐ 0
- ☐ 45
- ☐ 60
- ☐ 90



APPENDIX B: Glare Evaluation Process of Mt. Angel Abby Library

GLARE EVALUATION PROCESS

1- **Bracketed RAW images captured:**
f-stop:5.6
Shutter speed: 4” - 2” - 1” - 1/2 - 1/4 - 1/8 - 1/15 - 1/30 - 1/60 - 1/125 - 1/500
White balance: Daylight
ISO100

2- **Luminance values measured by the Gossen Luminance meter**.

3- **RAW images converted to JPEG.**

4- **JPEG images combined to HDR images in photosphere.**

5- **Calibration factor incorporated.**

6- **Vignetting correction in Radiance.**

```
$ pcomb -e 'sq(x):x*x;r=sqrt(sq(3.74/xres*x-1.87)+sq(2.48/yres*y-
1.24))' -e 'sf=0.0193*r^6 + 2E-11*r^5 + 0.0048*r^4 + 5E-10*r^3 +
0.0893*r^2 - 2E-09*r + 1.0012' -e
'ro=sf*ri(1);go=sf*gi(1);bo=sf*bi(1)' -o 1.hdr > corrected1.hdr
```

7- **The corrected HDR images were cleaned up by creating a mask in Radiance.**

```
$ pcomb -e 'Cx:xmax/2;Cy:ymax/2;R:Cx/1.87;sq(x):x*x' -e 'inC=sq(R)-
sq(x-Cx)-sq(y-Cy)' -e
'ro=if(inC,ri(1),0);go=if(inC,gi(1),0);bo=if(inC,bi(1),0)' -o
corrected1.hdr > cropped1.hdr
```

8- **HDR images were saved as false color images and LDR images.**

9- **Image size changed to be under 800X800 for Evalglare.**

```
$ getinfo -d cropped1.hdr

$ pfilt -x /8.1 -y /8.1 cropped1.hdr > cropped1_small.hdr

$ getinfo -d cropped1_small.hdr
```

10- **An absolute threshold of 2000 cd/m2 was used to find glare sources. “-G” cuts field of view according to Guth.**

```
$ evalglare -b 2000 -c 1-threshold.hdr  -G 2 -vta -vv 180 -vh 180
cropped1_small.hdr
```

11- **In another glare evaluation, the threshold for glare was defined as any pixel greater than 7-times the luminance of the average scene luminance.**

```
$ evalglare -b 7 -c 1-7times.hdr  -G 2 -vta -vv 180 -vh 180
cropped1_small.hdr
```

APPENDIX C: The 3-phase Method Simulation of Switchable Glass Louvers

THE 3-PHASE METHOD SIMULATION OF SWITCHABLE GLASS LOUVERS

1- The room model was created in Ecotect

2- The model was exported to Radiance

3- The LCD (250 cd/m2) material description was copied from Greg Ward's post in Radiance mailing list:
http://www.radiance-online.org/pipermail/radiance-general/2006-July/003845.html

4- The view files, front.vf and side.vf were created.

5- The "clerestories.rad" file was defined as follows:

```
void glow windowglow_C
0
0
4  1  1  1  0

windowglow_C polygon clerestory
0
0
12
        7.00000  3.90000  5.60000
        7.00000  3.90000  4.90000
        5.00000  3.9000  4.90000
        5.00000  3.9000  5.60000

windowglow_C polygon clerestory
0
0
12
        11.00000  3.9000  5.60000
        11.00000  3.9000  4.90000
        9.00000  3.9000  4.90000
        9.00000  3.9000  5.60000
```

6- The "windows.rad" file was defined as follows:

```
void glow windowglow_W
0
0
4  1  1  1  0

windowglow_W polygon window
0
0
12
        9.00000  3.9000  4.80000
        11.00000  3.9000  4.80000
        11.00000  3.9000  3.80000
        9.00000  3.9000  3.80000
```

```
windowglow_W polygon window
0
0
12
        5.00000  3.9000  4.80000
        7.00000  3.9000  4.80000
        7.00000  3.9000  3.80000
        5.00000  3.9000  3.80000
```

7- Sensor file

```
$ cnt 6 8 | rcalc -e '$1=$2+4.5;$2=$1+4.5;$3=3.86;$4=0;$5=0;$6=1'
> data/photocells.pts
```

8- View Matrix

```
$ oconv materials/room.mat objects/room.rad objects/windows.rad
objects/clerestories.rad objects/ground.rad > model_vmx.oct

$ rvu -ab 2 -vf views/front.vf model_vmx.oct

$ rcontrib -f klems_int.cal -bn Nkbins -fo -o
results/photocells_%s.vmx -b kbinS -m windowglow_W -b kbinS -m
windowglow_C -I+ -ab 12 -ad 50000 -lw 2e-5 model_vmx.oct <
data/photocells.pts

$ ulimit -n 512

$ vwrays -ff -vf views/front.vf -x 600 -y 600 | rcontrib `vwrays
-vf views/front.vf -x 600 -y 600 -d` -ffc -fo -o
images/vmx/%s_%03d.hdr -f klems_int.cal -bn Nkbins -b kbinS -m
windowglow_W -b kbinS -m windowglow_C -ab 12 -ad 50000 -lw 2e-5
model_vmx.oct
```

9- Daylight Matrix

```
$ oconv materials/room.mat objects/room.rad objects/ground.rad
objects/sky_white1.rad > model_dmx.oct

$ genklemsamp -vd 0 -1 0 objects/windows.rad | rcontrib -c 1000 -
e MF:4 -f reinhart.cal -b rbin -bn Nrbins -m sky_glow -faf
model_dmx.oct > results/windows.dmx

$ genklemsamp -vd 0 -1 0 objects/clerestories.rad | rcontrib -c
1000 -e MF:4 -f reinhart.cal -b rbin -bn Nrbins -m sky_glow -faf
model_dmx.oct > results/clerestories.dmx
```

10-Transmission matrices were created in LBNL Window program.

11- Sky Matrix

```
$ epw2wea USA_WI_Milwaukee_TMY3.epw Milwaukee.wea

$ gendaymtx -m 4 WEA/Milwaukee.wea > WEA/Milwaukee.smx
```

12- Hourly illuminance data

```
$ dctimestep -n 8760 results/photocells_windowglow_W.vmx xml/low-
e+venetain80.xml results/windows.dmx WEA/Milwaukee.smx >
results/illuminances/Milwaukee_Venetian80.txt
```

13- The .txt file were opened in text wrangler. Using search > find tool, \t was replaced with \n. The file was saved then the RGB values were converted to illuminance values using this command:

```
$ rcalc -e '$1=179*($1*0.265+$2*0.670+$3*0.065)'
results/illuminances/Milwaukee-Venetian80.txt >
results/illuminances/oneColumn/Milwaukee-Venetian80.txt
```

14- The resultant illuminance data were transferred to Excel for post-processing.

15- Sky vector

```
$ gensky 6 21 14 (you can add location: +s –a 42.95 –o 87.90)|
genskyvec -m 4 -c 1 1 1 > skies/6_21_14.skv

$ gensky 9 21 12 -c | genskyvec -m 4 -c 1 1 1 > skies/cloudy.skv
```

At first attempt, the rendered view did not show the LCD as a glow source. To include the LCD luminance (250 cd/m2), a Radiance image file was created with LCD only, and the LCD.hdr was combined to the rendered images:

```
$ oconv objects/LCD.rad > objects/LCD.oct

$ rpict -vf front.vf -x 600 -y 600 objects/LCD.oct > LCD.hdr
```

16- Renderings

```
$ pcomb '!dctimestep images/vmx/windowglow_W_%03d.hdr xml/low-
e+venetain80.xml results/windows.dmx skies/6_21_14.skv'
'!dctimestep images/vmx/windowglow_C_%03d.hdr xml/low-e+hazed-
lc.xml results/clerestories.dmx skies/6_21_14.skv' 'LCD.hdr' >
images/6_21_14-HazedLC.hdr

$ pcomb '!dctimestep images/vmx/windowglow_W_%03d.hdr xml/low-
e.xml results/windows.dmx skies/cloudy.skv' '!dctimestep
images/vmx/windowglow_C_%03d.hdr xml/low-e+clear-lc.xml
results/clerestories.dmx skies/cloudy.skv' 'LCD.hdr' >
images/ClearLC.hdr
```

17- Glare evaluation using Evalglare

```
$ evalglare -c checkfiles/ClearLC-task.hdr -T 300 247 .5 -vf
front.vf ClearLC.hdr > ClearLC-task.txt

$ evalglare -b 7 -c checkfiles/ClearLC-7times.hdr -vf front.vf
ClearLC.hdr > ClearLC-7times.txt
```

APPENDIX D: The 5-phase Method Simulation of Switchable Glass Louvers

THE 5-PHASE METHOD SIMULATION OF SWITCHABLE GLASS LOUVERS

1- Calculation of trans parameters for LC glass

1.1- Liquid Crystal Glass in Hazed State:

Visible Transmittance: 67%
Reflectance: 18%
Clarity (small-angle scattering): 4%
Thickness: 8mm

Ts = .04
Td = .67 - .04 = .63
Rd = .18
Rs = 0 (guessing no clear reflections)

A7 = Ts/(Td+Ts) = .04/(.63+.04) = .0597
A6 = (Td+Ts)/(Rd+Td+Ts) = (.63+.04)/(.18+.63+.04) = .7882
A5 = 0 (adjust if you want to scatter your transmitted rays a bit)
A4 = Rs = 0
A1 = A2 = A3 = .18/((1-0)(1-A6) = .18/(1-.7882) = .85 (assumes uncolored material)*

```
# Hazed-LC:
void trans hazedLC
0
0
7       0.85  0.85  0.85  0  0  0.7882  0.0597
```

1.2- Liquid Crystal Glass in Clear State:

Visible Transmittance: 75%
Reflectance: 14%
Clarity (small-angle scattering): 76%
Thickness: 8mm

Ts = 0.76
Td = 0.75 - 0.76 = -0.01
Rd = 0.14
Rs = 0 (guessing no clear reflections)

A7 = Ts/(Td+Ts) = .76/(-0.01+.76) = 1.01
A6 = (Td+Ts)/(Rd+Td+Ts) = .75/(.14+.75) = .8427
A5 = 0 (adjust if you want to scatter your transmitted rays a bit)
A4 = Rs = 0
A1 = A2 = A3 = .14/((1-0)(1-A6) = .14/(1-.8427) = .89 (assumes uncolored material)*

```
# Clear-LC:
void trans clearLC
0
0
7       0.89  0.89  0.89  0  0  0.8427  1.0
```

2- Creating BSDFs

```
cd bsdf

xform -rz 180 -rx -90 glazing.rad reveal.rad > reveal_glazing1.rad

xform -t 7 -3.8 -4 reveal_glazing1.rad > reveal_glazing.rad

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad venetian80.rad LChazed.rad > v80_LChazed_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad venetian80.rad LCclear.rad > v80_LCclear_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad venetian80.rad ECtinted.rad > v80_ECtinted_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad venetian80.rad ECclear.rad > v80_ECclear_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad venetian80.rad OpaqueLouver.rad > v80_opaque_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad LChazed.rad > noshade_LChazed_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad LCclear.rad > noshade_LCclear_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad ECtinted.rad > noshade_ECtinted_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad ECclear.rad > noshade_ECclear_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad OpaqueLouver.rad > noshade_opaque_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad venetian80.rad > v80_t45.xml

genBSDF -n 12 +f +b -geom meter -t4 5 -r "-ab 3 -ad 500 -lw 1e-5"
reveal_glazing.rad > Allclear_t45.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad venetian80.rad
LChazed.rad > v80_LChazed_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad venetian80.rad
LCclear.rad > v80_LCclear_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad venetian80.rad
ECtinted.rad > v80_ECtinted_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad venetian80.rad
ECclear.rad > v80_ECclear_klems.xml
```

```
genBSDF -n 12 +f +b -geom meter reveal_glazing.rad venetian80.rad
OpaqueLouver.rad > v80_opaque_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad LChazed.rad >
noshade_LChazed_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad LCclear.rad >
noshade_LCclear_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad ECtinted.rad >
noshade_ECtinted_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad ECclear.rad >
noshade_ECclear_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad OpaqueLouver.rad >
noshade_opaque_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad venetian80.rad >
v80_klems.xml

genBSDF -n 12 +f +b -geom meter reveal_glazing.rad > Allclear_klems.xml
```

3- BSDF Proxy

Example:

```
#objects/glazing_NTEC_bsdf.rad
void BSDF BSDFproxy
6 0.2 bsdf/noshade_ECtinted_t45.xml 0 0 1 .
0
0

BSDFproxy polygon inside1
0
0
12   7.00000  4.00000  5.60000
     7.00000  4.00000  3.80000
     5.00000  4.0000  3.80000
     5.00000  4.0000  5.60000


BSDFproxy polygon inside2
0
0
12   11.00000  4.0000  5.60000
     11.00000  4.0000  3.80000
     9.00000  4.0000  3.80000
     9.00000  4.0000  5.60000
```

4- View matrix (V)

```
oconv materials/room.mat objects/ground.rad objects/room.rad
objects/sky_white1.rad objects/viewmtxsurf.rad objects/daymtxsurf.rad >
octs/model_3ph.oct
```

```
rcontrib < data/photocells.pts -f klems_int.cal -b kbinS -bn Nkbins -m
viewsurf -I+ -ab 10 -ad 65536 -lw 1.52e-5 octs/model_3ph.oct >
matrices/viewmatrix.vmx
```

5- Direct view matrix (Vd)

```
rcontrib < data/photocells.pts -f klems_int.cal -b kbinS -bn Nkbins -m
viewsurf -I+ -ab 1 -ad 65536 -lw 1.52e-5 octs/model_3ph.oct >
matrices/viewmatrix_direct.vmx
```

6- Daylight matrix (D)

```
genklemsamp -c 1000 -vd 0 -1 0 objects/daymtxsurf.rad | rcontrib -c
1000 -ab 2 -ad 1024 -e MF:1 -f reinhart.cal -b rbin -bn Nrbins -m
sky_glow octs/model_3ph.oct > matrices/daylightmatrix.dmx
```

7- Direct daylight matrix (Dd)

7.1- All black model

```
xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/viewmtxsurf.rad objects/daymtxsurf.rad
objects/sky_white1.rad > octs/model_allblack.oct
```

7.2- Direct Daylight Martix

```
genklemsamp -c 1000 -vd 0 -1 0 objects/daymtxsurf.rad | rcontrib -c
1000 -ab 0 -e MF:1 -f reinhart.cal -b rbin -bn Nrbins -m sky_glow
octs/model_allblack.oct > matrices/daylightmatrix_direct.dmx
```

8- Direct sun coefficient matrix (Cds)

8.1- Suns model

```
echo void light solar 0 0 3 1e6 1e6 1e6 > skies/suns.rad

cnt 5185 | rcalc -e MF:6 -f
/Applications/Radiance/HEAD_2013_09_11/ray/lib/reinsrc.cal -e
Rbin=recno -o 'solar source sun 0 0 4 ${ Dx } ${ Dy } ${ Dz } 0.533' >>
skies/suns.rad
```

8.2- All black model

```
xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/venetian80.rad
objects/LChazed.rad objects/glazing_VHLC_bsdf.rad skies/suns.rad >
octs/model_suns_VHLC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/venetian80.rad
objects/LCclear.rad objects/glazing_VCLC_bsdf.rad skies/suns.rad >
octs/model_suns_VCLC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/venetian80.rad
objects/OpaqueLouver.rad objects/glazing_VO_bsdf.rad skies/suns.rad >
octs/model_suns_VO.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/LChazed.rad
objects/glazing_NHLC_bsdf.rad skies/suns.rad > octs/model_suns_NHLC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
```

```
materials/room.mat - objects/glazing.rad objects/LCclear.rad
objects/glazing_NCLC_bsdf.rad skies/suns.rad > octs/model_suns_NCLC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/OpaqueLouver.rad
objects/glazing_NO_bsdf.rad skies/suns.rad > octs/model_suns_NO.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/venetian80.rad
objects/ECtinted.rad objects/glazing_VTEC_bsdf.rad skies/suns.rad >
octs/model_suns_VTEC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/venetian80.rad
objects/ECclear.rad objects/glazing_VCEC_bsdf.rad skies/suns.rad >
octs/model_suns_VCEC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/ECtinted.rad
objects/glazing_NTEC_bsdf.rad skies/suns.rad > octs/model_suns_NTEC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/ECclear.rad
objects/glazing_NCEC_bsdf.rad skies/suns.rad > octs/model_suns_NCEC.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad objects/venetian80.rad
objects/glazing_V80_bsdf.rad skies/suns.rad > octs/model_suns_V80.oct

xform -m black objects/room.rad objects/ground.rad | oconv
materials/room.mat - objects/glazing.rad
objects/glazing_Allclear_bsdf.rad skies/suns.rad >
octs/model_suns_Allclear.oct
```

8.3- Sun coefficient matrix

```
rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_VHLC.oct > matrices/directsun_VHLC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_VCLC.oct > matrices/directsun_VCLC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_VO.oct > matrices/directsun_VO.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_NHLC.oct > matrices/directsun_NHLC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_NCLC.oct > matrices/directsun_NCLC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
```

```
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_NO.oct > matrices/directsun_NO.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_VTEC.oct > matrices/directsun_VTEC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_VCEC.oct > matrices/directsun_VCEC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_NTEC.oct > matrices/directsun_NTEC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_NCEC.oct > matrices/directsun_NCEC.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_V80.oct > matrices/directsun_V80.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_Allclear.oct > matrices/directsun_Allclear.dsmx
```

9- Putting it all together

9.1- Weather files

```
gendaymtx -of WEA/Milwaukee.wea > matrices/Milwaukee.smx
gendaymtx -of -d WEA/Milwaukee.wea > matrices/Milwaukee_direct.smx
gendaymtx -5 -d -m 6 -of WEA/Milwaukee.wea >
matrices/Milwaukee_direct_m6.smx

gendaymtx -of WEA/Dallas.wea > matrices/Dallas.smx
gendaymtx -of -d WEA/Dallas.wea > matrices/Dallas_direct.smx
gendaymtx -5 -d -m 6 -of WEA/Dallas.wea > matrices/Dallas_direct_m6.smx

gendaymtx -of WEA/Phoenix.wea > matrices/Phoenix.smx
gendaymtx -of -d WEA/Phoenix.wea > matrices/Phoenix_direct.smx
gendaymtx -5 -d -m 6 -of WEA/Phoenix.wea >
matrices/Phoenix_direct_m6.smx

gendaymtx -of WEA/SanFrancisco.wea > matrices/SanFrancisco.smx
gendaymtx -of -d WEA/SanFrancisco.wea >
matrices/SanFrancisco_direct.smx
gendaymtx -5 -d -m 6 -of WEA/SanFrancisco.wea >
matrices/SanFrancisco_direct_m6.smx

gendaymtx -of WEA/Seattle.wea > matrices/Seattle.smx
gendaymtx -of -d WEA/Seattle.wea > matrices/Seattle_direct.smx
gendaymtx -5 -d -m 6 -of WEA/Seattle.wea >
matrices/Seattle_direct_m6.smx
```

9.2- First term

```
dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/v80_LChazed_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_VHLC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/v80_LCclear_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_VCLC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/v80_opaque_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_VO.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/noshade_LChazed_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_NHLC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/noshade_LCclear_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_NCLC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/noshade_opaque_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_NO.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/v80_ECtinted_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_VTEC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/v80_ECclear_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_VCEC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/noshade_ECtinted_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_NTEC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx
bsdf/noshade_ECclear_klems.xml matrices/daylightmatrix.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/i_3ph_Milwaukee_NCEC.txt

dctimestep -n 8760 -if matrices/viewmatrix.vmx bsdf/v80_klems.xml
matrices/daylightmatrix.dmx matrices/Milwaukee.smx | rcollate -h -oc 1
> terms/i_3ph_Milwaukee_V80.txt
```

```
dctimestep -n 8760 -if matrices/viewmatrix.vmx bsdf/Allclear_klems.xml
matrices/daylightmatrix.dmx matrices/Milwaukee.smx | rcollate -h -oc 1
> terms/i_3ph_Milwaukee_Allclear.txt
```

9.3- Second term

```
dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/v80_LChazed_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_VHLC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/v80_LCclear_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_VCLC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/v80_opaque_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_VO.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/noshade_LChazed_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_NHLC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/noshade_LCclear_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_NCLC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/noshade_opaque_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_NO.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/v80_ECtinted_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_VTEC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/v80_ECclear_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_VCEC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/noshade_ECtinted_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_NTEC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/noshade_ECclear_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_NCEC.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
```

```
bsdf/v80_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_V80.txt

dctimestep -n 8760 -if matrices/viewmatrix_direct.vmx
bsdf/Allclear_klems.xml matrices/daylightmatrix_direct.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/i_ds3ph_Milwaukee_Allclear.txt
```

9.4- Third term

```
dctimestep -n 8760 -if matrices/directsun_VHLC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_VHLC.txt

dctimestep -n 8760 -if matrices/directsun_VCLC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_VCLC.txt

dctimestep -n 8760 -if matrices/directsun_VO.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_VO.txt

dctimestep -n 8760 -if matrices/directsun_NHLC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_NHLC.txt

dctimestep -n 8760 -if matrices/directsun_NCLC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_NCLC.txt

dctimestep -n 8760 -if matrices/directsun_NO.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_NO.txt

dctimestep -n 8760 -if matrices/directsun_VTEC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_VTEC.txt

dctimestep -n 8760 -if matrices/directsun_VCEC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_VCEC.txt

dctimestep -n 8760 -if matrices/directsun_NTEC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_NTEC.txt

dctimestep -n 8760 -if matrices/directsun_NCEC.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_NCEC.txt

dctimestep -n 8760 -if matrices/directsun_V80.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Milwaukee_V80.txt

dctimestep -n 8760 -if matrices/directsun_Allclear.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
```

terms/i_ds5ph_Milwaukee_Allclear.txt

9.5- Combing the three terms using rlam tool

```
rlam terms/i_3ph_Milwaukee_VHLC.txt terms/i_ds3ph_Milwaukee_VHLC.txt
terms/i_ds5ph_Milwaukee_VHLC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_VHLC.txt

rlam terms/i_3ph_Milwaukee_VCLC.txt terms/i_ds3ph_Milwaukee_VCLC.txt
terms/i_ds5ph_Milwaukee_VCLC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_VCLC.txt

rlam terms/i_3ph_Milwaukee_VO.txt terms/i_ds3ph_Milwaukee_VO.txt
terms/i_ds5ph_Milwaukee_VO.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_Milwaukee_VO.txt

rlam terms/i_3ph_Milwaukee_NHLC.txt terms/i_ds3ph_Milwaukee_NHLC.txt
terms/i_ds5ph_Milwaukee_NHLC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_NHLC.txt

rlam terms/i_3ph_Milwaukee_NCLC.txt terms/i_ds3ph_Milwaukee_NCLC.txt
terms/i_ds5ph_Milwaukee_NCLC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_NCLC.txt

rlam terms/i_3ph_Milwaukee_NO.txt terms/i_ds3ph_Milwaukee_NO.txt
terms/i_ds5ph_Milwaukee_NO.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_Milwaukee_NO.txt

rlam terms/i_3ph_Milwaukee_VTEC.txt terms/i_ds3ph_Milwaukee_VTEC.txt
terms/i_ds5ph_Milwaukee_VTEC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_VTEC.txt

rlam terms/i_3ph_Milwaukee_VCEC.txt terms/i_ds3ph_Milwaukee_VCEC.txt
terms/i_ds5ph_Milwaukee_VCEC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_VCEC.txt

rlam terms/i_3ph_Milwaukee_NTEC.txt terms/i_ds3ph_Milwaukee_NTEC.txt
terms/i_ds5ph_Milwaukee_NTEC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_NTEC.txt

rlam terms/i_3ph_Milwaukee_NCEC.txt terms/i_ds3ph_Milwaukee_NCEC.txt
terms/i_ds5ph_Milwaukee_NCEC.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_NCEC.txt

rlam terms/i_3ph_Milwaukee_V80.txt terms/i_ds3ph_Milwaukee_V80.txt
terms/i_ds5ph_Milwaukee_V80.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
```

```
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_Milwaukee_V80.txt

rlam terms/i_3ph_Milwaukee_Allclear.txt
terms/i_ds3ph_Milwaukee_Allclear.txt
terms/i_ds5ph_Milwaukee_Allclear.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t > results/illum_Milwaukee_Allclear.txt
```

10- The data were transferred to Excel for post-processing.

APPENDIX E: The 5-phase Method Simulation of Studio 406 Windows

THE 5-PHASE METHOD SIMULATION OF STUDIO 406 WINDOWS

1- Creating BSDFs

1.1 Existing Design:

```
genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad >
bsdf/Window_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0
materials/AUP406.mat objects/window/Exist_Window.rad >
bsdf/Window_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/V80_all.rad > bsdf/V80_all_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/V80_all.rad > bsdf/V80_all_klems.xml
```

1.2 Exterior shading - West windows

```
genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/lightshelf_west.rad >
bsdf/W_extDown_noblind_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/lightshelf_west.rad >
bsdf/W_extDown_noblind_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/V80_half.rad
objects/window/lightshelf_west.rad > bsdf/W_extDown_V80_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/V80_half.rad
objects/window/lightshelf_west.rad > bsdf/W_extDown_V80_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad objects/window/V80_half.rad
objects/window/lightshelf_west.rad > bsdf/W_extUp_V80_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad objects/window/V80_half.rad
objects/window/lightshelf_west.rad > bsdf/W_extUp_V80_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad
objects/window/lightshelf_west.rad > bsdf/W_ext_allOpen_t45.xml
```

```
genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -1.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad
objects/window/lightshelf_west.rad > bsdf/W_ext_allOpen_klems.xml
```

1.3 Exterior shading - South windows

```
genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/lightshelf_south.rad >
bsdf/S_extDown_noblind_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/lightshelf_south.rad >
bsdf/S_extDown_noblind_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/V80_half.rad
objects/window/lightshelf_south.rad > bsdf/S_extDown_V80_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_45.rad objects/window/V80_half.rad
objects/window/lightshelf_south.rad > bsdf/S_extDown_V80_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad objects/window/V80_half.rad
objects/window/lightshelf_south.rad > bsdf/S_extUp_V80_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad objects/window/V80_half.rad
objects/window/lightshelf_south.rad > bsdf/S_extUp_V80_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad
objects/window/lightshelf_south.rad > bsdf/S_ext_allOpen_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.91 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/ext_louver_retracted.rad
objects/window/lightshelf_south.rad > bsdf/S_ext_allOpen_klems.xml
```

1.4 Interior shading

```
genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_45.rad > bsdf/int_louver_noblind_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_45.rad > bsdf/int_louver_noblind_klems.xml
```

```
genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_45.rad objects/window/V80_half.rad >
bsdf/int_louver_V80_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_45.rad objects/window/V80_half.rad >
bsdf/int_louver_V80_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_retracted.rad objects/window/V80_half.rad >
bsdf/int_retracted_V80_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_retracted.rad objects/window/V80_half.rad >
bsdf/int_retracted_V80_klems.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0 -t4 5
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_retracted.rad > bsdf/int_allOpen_t45.xml

genBSDF -n 12 +f +b -geom meter -dim 0 2.42 0 2.79 -.41 0
materials/AUP406.mat objects/window/Exist_Window.rad
objects/window/int_louver_retracted.rad > bsdf/int_allOpen_klems.xml
```

2- BSDF Proxy

Example:

```
#objects/proxy/N_windowPrx.rad
void BSDF BSDFproxy
6 0.41 bsdf/Window_t45.xml 0 0 1 .
0
0

BSDFproxy polygon zone06.rad00981
0
0
12
      4.03800  24.58200  12.64000
      4.03800  24.58200  15.43000
      1.61800  24.58200  15.43000
      1.61800  24.58200  12.64000

BSDFproxy polygon zone06.rad00982
0
0
12
      5.89800  24.58200  12.64000
      8.31800  24.58200  12.64000
      8.31800  24.58200  15.43000
      5.89800  24.58200  15.43000
```

3- View Matrix

```
oconv materials/AUP406.mat objects/ground.rad objects/room/room.rad
objects/sky_white1.rad objects/viewmtxsurf/viewmtxsurf_south.rad
objects/viewmtxsurf/viewmtxsurf_west.rad
objects/viewmtxsurf/viewmtxsurf_north.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad > octs/model_3ph.oct

rcontrib -f klems_int.cal -bn Nkbins -fo -o matrices/photocells_%s.vmx
-b kbinS -m viewsurf_south -b kbinW -m viewsurf_west -b kbinN -m
viewsurf_north -I+ -ab 10 -ad 65536 -lw 1.52e-5 octs/model_3ph.oct <
data/photocells.pts
```

4- Direct View Matrix

```
rcontrib -f klems_int.cal -bn Nkbins -fo -o matrices/direct_%s.vmx -b
kbinS -m viewsurf_south -b kbinW -m viewsurf_west -b kbinN -m
viewsurf_north -I+ -ab 1 -ad 65536 -lw 1.52e-5 octs/model_3ph.oct <
data/photocells.pts
```

5- Daylight Matrix

```
genklemsamp -c 1000 -vd 0 -1 0 objects/daymtxsurf/daymtxsurf_south.rad
| rcontrib -c 1000 -ab 2 -ad 1024 -e MF:1 -f reinhart.cal -b rbin -bn
Nrbins -m sky_glow octs/model_3ph.oct >
matrices/daylightmatrix_south.dmx

genklemsamp -c 1000 -vd -1 0 0 objects/daymtxsurf/daymtxsurf_west.rad |
rcontrib -c 1000 -ab 2 -ad 1024 -e MF:1 -f reinhart.cal -b rbin -bn
Nrbins -m sky_glow octs/model_3ph.oct >
matrices/daylightmatrix_west.dmx

genklemsamp -c 1000 -vd 0 1 0 objects/daymtxsurf/daymtxsurf_north.rad |
rcontrib -c 1000 -ab 2 -ad 1024 -e MF:1 -f reinhart.cal -b rbin -bn
Nrbins -m sky_glow octs/model_3ph.oct >
matrices/daylightmatrix_north.dmx
```

6- Direct Daylight Matrix

```
xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/viewmtxsurf/viewmtxsurf_south.rad
objects/viewmtxsurf/viewmtxsurf_west.rad
objects/viewmtxsurf/viewmtxsurf_north.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad objects/sky_white1.rad >
octs/allblack_model.oct

genklemsamp -c 1000 -vd 0 -1 0 objects/daymtxsurf/daymtxsurf_south.rad
| rcontrib -c 1000 -ab 0 -e MF:1 -f reinhart.cal -b rbin -bn Nrbins -m
sky_glow octs/allblack_model.oct >
matrices/daylightmatrix_direct_south.dmx

genklemsamp -c 1000 -vd -1 0 0 objects/daymtxsurf/daymtxsurf_west.rad |
rcontrib -c 1000 -ab 0 -e MF:1 -f reinhart.cal -b rbin -bn Nrbins -m
sky_glow octs/allblack_model.oct >
matrices/daylightmatrix_direct_west.dmx
```

```
genklemsamp -c 1000 -vd 0 1 0 objects/daymtxsurf/daymtxsurf_north.rad |
rcontrib -c 1000 -ab 0 -e MF:1 -f reinhart.cal -b rbin -bn Nrbins -m
sky_glow octs/allblack_model.oct >
matrices/daylightmatrix_direct_north.dmx
```

7- Direct Sun Coefficient Matrix

7.1. suns model

```
echo void light solar 0 0 3 1e6 1e6 1e6 > skies/suns.rad

cnt 5185 | rcalc -e MF:6 -f
/Applications/Radiance/HEAD_2013_09_11/ray/lib/reinsrc.cal -e
Rbin=recno -o 'solar source sun 0 0 4 ${ Dx } ${ Dy } ${ Dz } 0.533' >>
skies/suns.rad
```

7.2. All black model

```
xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_windowPrx.rad objects/proxy/W_windowPrx.rad
skies/suns.rad > octs/model_suns_Window.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_venetian80_all.rad
objects/room/W_venetian80_all.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_V80allPrx.rad objects/proxy/W_V80allPrx.rad
skies/suns.rad > octs/model_suns_V80all.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_venetian80_all.rad
objects/proxy/N_windowPrx.rad objects/proxy/S_V80allPrx.rad
objects/proxy/W_windowPrx.rad skies/suns.rad >
octs/model_suns_S_V80all.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_venetian80_all.rad
objects/proxy/N_windowPrx.rad objects/proxy/S_windowPrx.rad
objects/proxy/W_V80allPrx.rad skies/suns.rad >
octs/model_suns_W_V80all.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers_retracted.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/S_ext_allOpenPrx.rad
objects/proxy/W_ext_allOpenPrx.rad skies/suns.rad >
octs/model_suns_ext_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
```

```
objects/proxy/N_windowPrx.rad objects/proxy/S_extDown_noblindPrx.rad
objects/proxy/W_ext_allOpenPrx.rad skies/suns.rad >
octs/model_suns_ext_S_louver_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_ext_louvers.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/W_extDown_noblindPrx.rad
objects/proxy/S_ext_allOpenPrx.rad skies/suns.rad >
octs/model_suns_ext_W_louver_S_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers.rad
objects/room/S_venetian80_half.rad objects/room/W_ext_louvers.rad
objects/room/W_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_extDown_V80Prx.rad objects/proxy/W_extDown_V80Prx.rad
skies/suns.rad > octs/model_suns_ext_allClosed.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers.rad
objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_extDown_V80Prx.rad objects/proxy/W_extUp_V80Prx.rad
skies/suns.rad > octs/model_suns_ext_S_allClosed_W_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_ext_louvers.rad
objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/S_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/proxy/N_windowPrx.rad
objects/proxy/W_extDown_V80Prx.rad objects/proxy/S_extUp_V80Prx.rad
skies/suns.rad > octs/model_suns_ext_W_allClosed_S_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers.rad
objects/room/S_venetian80_half.rad objects/room/W_ext_louvers.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/S_extDown_V80Prx.rad
objects/proxy/W_extDown_noblindPrx.rad skies/suns.rad >
octs/model_suns_ext_S_allClosed_W_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_ext_louvers.rad
objects/room/W_venetian80_half.rad objects/room/S_ext_louvers.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/W_extDown_V80Prx.rad
```

```
objects/proxy/S_extDown_noblindPrx.rad skies/suns.rad >
octs/model_suns_ext_W_allClosed_S_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/S_extUp_V80Prx.rad
objects/proxy/W_ext_allOpenPrx.rad skies/suns.rad >
octs/model_suns_ext_S_V80half_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/W_extUp_V80Prx.rad
objects/proxy/S_ext_allOpenPrx.rad skies/suns.rad >
octs/model_suns_ext_W_V80half_S_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers.rad
objects/room/W_ext_louvers.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_extDown_noblindPrx.rad
objects/proxy/W_extDown_noblindPrx.rad skies/suns.rad >
octs/model_suns_ext_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/proxy/N_windowPrx.rad
objects/proxy/W_extUp_V80Prx.rad objects/proxy/S_extUp_V80Prx.rad
skies/suns.rad > octs/model_suns_ext_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_ext_louvers.rad
objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/S_extDown_V80Prx.rad
objects/proxy/W_ext_allOpenPrx.rad skies/suns.rad >
octs/model_suns_ext_S_allClosed_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_ext_louvers.rad
objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers_retracted.rad
```

```
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/proxy/N_windowPrx.rad objects/proxy/W_extDown_V80Prx.rad
objects/proxy/S_ext_allOpenPrx.rad skies/suns.rad >
octs/model_suns_ext_W_allClosed_S_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers_retracted.rad
objects/room/W_int_louvers_retracted.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_int_allOpenPrx.rad objects/proxy/W_int_allOpenPrx.rad
skies/suns.rad > octs/model_suns_int_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers.rad
objects/room/W_int_louvers_retracted.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_intClosed_noblindPrx.rad
objects/proxy/W_int_allOpenPrx.rad skies/suns.rad >
octs/model_suns_int_S_louver_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_int_louvers.rad
objects/room/S_int_louvers_retracted.rad objects/proxy/N_windowPrx.rad
objects/proxy/W_intClosed_noblindPrx.rad
objects/proxy/S_int_allOpenPrx.rad skies/suns.rad >
octs/model_suns_int_W_louver_S_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers.rad
objects/room/S_venetian80_half.rad objects/room/W_int_louvers.rad
objects/room/W_venetian80_half.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_intClosed_V80Prx.rad
objects/proxy/W_intClosed_V80Prx.rad skies/suns.rad >
octs/model_suns_int_allClosed.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_intClosed_V80Prx.rad objects/proxy/W_intOpen_V80Prx.rad
skies/suns.rad > octs/model_suns_int_S_allClosed_W_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_int_louvers.rad
objects/room/W_venetian80_half.rad
objects/room/S_int_louvers_retracted.rad
objects/room/S_venetian80_half.rad objects/proxy/N_windowPrx.rad
objects/proxy/W_intClosed_V80Prx.rad objects/proxy/S_intOpen_V80Prx.rad
skies/suns.rad > octs/model_suns_int_W_allClosed_S_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
```

```
objects/room/windowFrame.rad objects/room/S_int_louvers.rad
objects/room/S_venetian80_half.rad objects/room/W_int_louvers.rad
objects/proxy/N_windowPrx.rad objects/proxy/S_intClosed_V80Prx.rad
objects/proxy/W_intClosed_noblindPrx.rad skies/suns.rad >
octs/model_suns_int_S_allClosed_W_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_int_louvers.rad
objects/room/W_venetian80_half.rad objects/room/S_int_louvers.rad
objects/proxy/N_windowPrx.rad objects/proxy/W_intClosed_V80Prx.rad
objects/proxy/S_intClosed_noblindPrx.rad skies/suns.rad >
octs/model_suns_int_W_allClosed_S_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_intOpen_V80Prx.rad objects/proxy/W_int_allOpenPrx.rad
skies/suns.rad > octs/model_suns_int_S_V80half_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/W_int_louvers_retracted.rad
objects/room/W_venetian80_half.rad
objects/room/S_int_louvers_retracted.rad objects/proxy/N_windowPrx.rad
objects/proxy/W_intOpen_V80Prx.rad objects/proxy/S_int_allOpenPrx.rad
skies/suns.rad > octs/model_suns_int_W_V80half_S_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_intOpen_V80Prx.rad objects/proxy/W_intOpen_V80Prx.rad
skies/suns.rad > octs/model_suns_int_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers.rad
objects/room/W_int_louvers.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_intClosed_noblindPrx.rad
objects/proxy/W_intClosed_noblindPrx.rad skies/suns.rad >
octs/model_suns_int_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
objects/room/windowFrame.rad objects/room/S_int_louvers.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad objects/proxy/N_windowPrx.rad
objects/proxy/S_intClosed_V80Prx.rad objects/proxy/W_int_allOpenPrx.rad
skies/suns.rad > octs/model_suns_int_S_allClosed_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/glazing.rad
```

```
objects/room/windowFrame.rad objects/room/W_int_louvers.rad
objects/room/W_venetian80_half.rad
objects/room/S_int_louvers_retracted.rad objects/proxy/N_windowPrx.rad
objects/proxy/W_intClosed_V80Prx.rad objects/proxy/S_int_allOpenPrx.rad
skies/suns.rad > octs/model_suns_int_W_allClosed_S_allOpen.oct
```

7.3. DirectSun Matrix

```
rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_allClosed.oct >
matrices/directsun_ext_allClosed.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_allOpen.oct >
matrices/directsun_ext_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_S_allClosed_W_louvers.oct >
matrices/directsun_ext_S_allClosed_W_louvers.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_S_allClosed_W_V80half.oct >
matrices/directsun_ext_S_allClosed_W_V80half.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_S_louver_W_allOpen.oct >
matrices/directsun_ext_S_louver_W_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_S_V80half_W_allOpen.oct >
matrices/directsun_ext_S_V80half_W_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_W_allClosed_S_louvers.oct >
matrices/directsun_ext_W_allClosed_S_louvers.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_W_allClosed_S_V80half.oct >
matrices/directsun_ext_W_allClosed_S_V80half.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_W_louver_S_allOpen.oct >
matrices/directsun_ext_W_louver_S_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_W_V80half_S_allOpen.oct >
matrices/directsun_ext_W_V80half_S_allOpen.dsmx
```

```
rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_louvers.oct >
matrices/directsun_ext_louvers.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_V80half.oct >
matrices/directsun_ext_V80half.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_S_allClosed_W_allOpen.oct >
matrices/directsun_ext_S_allClosed_W_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_ext_W_allClosed_S_allOpen.oct >
matrices/directsun_ext_W_allClosed_S_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_allClosed.oct >
matrices/directsun_int_allClosed.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_allOpen.oct >
matrices/directsun_int_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_S_allClosed_W_louvers.oct >
matrices/directsun_int_S_allClosed_W_louvers.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_S_allClosed_W_V80half.oct >
matrices/directsun_int_S_allClosed_W_V80half.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_S_louver_W_allOpen.oct >
matrices/directsun_int_S_louver_W_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_S_V80half_W_allOpen.oct >
matrices/directsun_int_S_V80half_W_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_W_allClosed_S_louvers.oct >
matrices/directsun_int_W_allClosed_S_louvers.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
```

```
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_W_allClosed_S_V80half.oct >
matrices/directsun_int_W_allClosed_S_V80half.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_W_louver_S_allOpen.oct >
matrices/directsun_int_W_louver_S_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_W_V80half_S_allOpen.oct >
matrices/directsun_int_W_V80half_S_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_V80half.oct >
matrices/directsun_int_V80half.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_louvers.oct >
matrices/directsun_int_louvers.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_S_allClosed_W_allOpen.oct >
matrices/directsun_int_S_allClosed_W_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_int_W_allClosed_S_allOpen.oct >
matrices/directsun_int_W_allClosed_S_allOpen.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_S_V80all.oct > matrices/directsun_S_V80al.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_V80all.oct > matrices/directsun_V80all.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_W_V80all.oct > matrices/directsun_W_V80all.dsmx

rcontrib < data/photocells.pts -I -ab 1 -ad 65536 -lw 1.52e-5 -dc 1 -dt
0 -dj 0 -st 1 -ss 0 -faf -e MF:6 -f reinhart.cal -b rbin -bn Nrbins -m
solar octs/model_suns_Window.oct > matrices/directsun_Window.dsmx
```

8. Putting it all together

8.1. Weather files

```
gendaymtx -of WEA/Milwaukee.wea > matrices/Milwaukee.smx
gendaymtx -of -d WEA/Milwaukee.wea > matrices/Milwaukee_direct.smx
gendaymtx -5 -d -m 6 -of WEA/Milwaukee.wea >
```

```
matrices/Milwaukee_direct_m6.smx
```

8.2. First Term
8.2.1 First Term1

```
dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/int_allOpen_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_int_allOpen.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/int_louver_noblind_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_int_louver_noblind.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/int_louver_V80_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_int_louver_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/int_retracted_V80_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_int_retracted_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/int_allOpen_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_int_allOpen.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/int_louver_noblind_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_int_louver_noblind.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/int_louver_V80_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_int_louver_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/int_retracted_V80_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_int_retracted_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/S_ext_allOpen_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_ext_allOpen.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/S_extDown_noblind_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_extDown_noblind.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/S_extDown_V80_klems.xml matrices/daylightmatrix_south.dmx
```

```
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_extDown_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/S_extUp_V80_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/S_extUp_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/V80_all_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 > terms/first/S_V80_all.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/V80_all_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 > terms/first/W_V80_all.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/W_ext_allOpen_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_ext_allOpen.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/W_extDown_noblind_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_extDown_noblind.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/W_extDown_V80_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_extDown_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/W_extUp_V80_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 >
terms/first/W_extUp_V80.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_north.vmx
bsdf/Window_klems.xml matrices/daylightmatrix_north.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 > terms/first/N_Window.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_south.vmx
bsdf/Window_klems.xml matrices/daylightmatrix_south.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 > terms/first/S_Window.txt

dctimestep -n 8760 -if matrices/photocells_viewsurf_west.vmx
bsdf/Window_klems.xml matrices/daylightmatrix_west.dmx
matrices/Milwaukee.smx | rcollate -h -oc 1 > terms/first/W_Window.txt
```

8.2.2 First Term2

```
rlam  terms/first/S_extDown_V80.txt terms/first/W_extDown_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_ext_allClosed.txt

rlam  terms/first/S_ext_allOpen.txt terms/first/W_ext_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_ext_allOpen.txt
```

```
rlam  terms/first/S_extDown_V80.txt terms/first/W_extDown_noblind.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_S_allClosed_W_louvers.txt

rlam  terms/first/S_extDown_V80.txt terms/first/W_extUp_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_S_allClosed_W_V80half.txt

rlam  terms/first/S_extDown_noblind.txt terms/first/W_ext_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_S_louver_W_allOpen.txt

rlam  terms/first/S_extUp_V80.txt terms/first/W_ext_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_S_V80half_W_allOpen.txt

rlam  terms/first/S_extDown_noblind.txt terms/first/W_extDown_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_W_allClosed_S_louvers.txt

rlam  terms/first/S_extUp_V80.txt terms/first/W_extDown_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_W_allClosed_S_V80half.txt

rlam  terms/first/S_ext_allOpen.txt terms/first/W_extDown_noblind.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_W_louver_S_allOpen.txt

rlam  terms/first/S_ext_allOpen.txt terms/first/W_extUp_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_W_V80half_S_allOpen.txt

rlam  terms/first/S_extDown_noblind.txt
terms/first/W_extDown_noblind.txt terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_ext_louvers.txt

rlam  terms/first/S_extUp_V80.txt terms/first/W_extUp_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_ext_V80half.txt

rlam  terms/first/S_extDown_V80.txt terms/first/W_ext_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_ext_S_allClosed_W_allOpen.txt

rlam  terms/first/W_extDown_V80.txt terms/first/S_ext_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
```

```
terms/i_3ph_ext_W_allClosed_S_allOpen.txt

rlam  terms/first/S_int_louver_V80.txt terms/first/W_int_louver_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_int_allClosed.txt

rlam  terms/first/S_int_allOpen.txt terms/first/W_int_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_int_allOpen.txt

rlam  terms/first/S_int_louver_V80.txt
terms/first/W_int_louver_noblind.txt terms/first/N_Window.txt |  rcalc
-e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_S_allClosed_W_louvers.txt

rlam  terms/first/S_int_louver_V80.txt
terms/first/W_int_retracted_V80.txt terms/first/N_Window.txt |  rcalc -
e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_S_allClosed_W_V80half.txt

rlam  terms/first/S_int_louver_noblind.txt
terms/first/W_int_allOpen.txt terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_S_louver_W_allOpen.txt

rlam  terms/first/S_int_retracted_V80.txt terms/first/W_int_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_S_V80half_W_allOpen.txt

rlam  terms/first/S_int_louver_noblind.txt
terms/first/W_int_louver_V80.txt terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_W_allClosed_S_louvers.txt

rlam  terms/first/S_int_retracted_V80.txt
terms/first/W_int_louver_V80.txt terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_W_allClosed_S_V80half.txt

rlam  terms/first/S_int_allOpen.txt
terms/first/W_int_louver_noblind.txt terms/first/N_Window.txt |  rcalc
-e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_W_louver_S_allOpen.txt

rlam  terms/first/S_int_allOpen.txt terms/first/W_int_retracted_V80.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_W_V80half_S_allOpen.txt

rlam  terms/first/S_int_louver_noblind.txt
terms/first/W_int_louver_noblind.txt terms/first/N_Window.txt |  rcalc
-e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_int_louvers.txt

rlam  terms/first/S_int_retracted_V80.txt
terms/first/W_int_retracted_V80.txt terms/first/N_Window.txt |  rcalc -
e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_int_V80half.txt
```

```
rlam  terms/first/S_int_louver_V80.txt terms/first/W_int_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_S_allClosed_W_allOpen.txt

rlam  terms/first/W_int_louver_V80.txt terms/first/S_int_allOpen.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_3ph_int_W_allClosed_S_allOpen.txt

rlam  terms/first/S_V80_all.txt terms/first/W_Window.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_S_V80all.txt

rlam  terms/first/S_V80_all.txt terms/first/W_V80_all.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_V80all.txt

rlam  terms/first/S_Window.txt terms/first/W_V80_all.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_W_V80all.txt

rlam  terms/first/S_Window.txt terms/first/W_Window.txt
terms/first/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_3ph_Window.txt
```

8.3. Second Term

8.3.1 Second Term1

```
dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/int_allOpen_klems.xml matrices/daylightmatrix_direct_south.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/S_int_allOpen.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_direct_south.dmx matrices/Milwaukee_direct.smx
| rcollate -h -oc 1 > terms/second/S_int_louver_noblind.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/int_louver_V80_klems.xml matrices/daylightmatrix_direct_south.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/S_int_louver_V80.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx matrices/Milwaukee_direct.smx
| rcollate -h -oc 1 > terms/second/S_int_retracted_V80.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/int_allOpen_klems.xml matrices/daylightmatrix_direct_west.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/W_int_allOpen.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/int_louver_noblind_klems.xml
```

```
matrices/daylightmatrix_direct_west.dmx matrices/Milwaukee_direct.smx |
rcollate -h -oc 1 > terms/second/W_int_louver_noblind.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/int_louver_V80_klems.xml matrices/daylightmatrix_direct_west.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/W_int_louver_V80.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx matrices/Milwaukee_direct.smx |
rcollate -h -oc 1 > terms/second/W_int_retracted_V80.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/S_ext_allOpen_klems.xml matrices/daylightmatrix_direct_south.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/S_ext_allOpen.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/S_extDown_noblind_klems.xml
matrices/daylightmatrix_direct_south.dmx matrices/Milwaukee_direct.smx
| rcollate -h -oc 1 > terms/second/S_extDown_noblind.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/S_extDown_V80_klems.xml matrices/daylightmatrix_direct_south.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/S_extDown_V80.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/S_extUp_V80_klems.xml matrices/daylightmatrix_direct_south.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/S_extUp_V80.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/V80_all_klems.xml matrices/daylightmatrix_direct_south.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/S_V80_all.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/V80_all_klems.xml matrices/daylightmatrix_direct_west.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/W_V80_all.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/W_ext_allOpen_klems.xml matrices/daylightmatrix_direct_west.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/W_ext_allOpen.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/W_extDown_noblind_klems.xml
matrices/daylightmatrix_direct_west.dmx matrices/Milwaukee_direct.smx |
rcollate -h -oc 1 > terms/second/W_extDown_noblind.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/W_extDown_V80_klems.xml matrices/daylightmatrix_direct_west.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/W_extDown_V80.txt
```

```
dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/W_extUp_V80_klems.xml matrices/daylightmatrix_direct_west.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/W_extUp_V80.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_north.vmx
bsdf/Window_klems.xml matrices/daylightmatrix_direct_north.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/N_Window.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_south.vmx
bsdf/Window_klems.xml matrices/daylightmatrix_direct_south.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/S_Window.txt

dctimestep -n 8760 -if matrices/direct_viewsurf_west.vmx
bsdf/Window_klems.xml matrices/daylightmatrix_direct_west.dmx
matrices/Milwaukee_direct.smx | rcollate -h -oc 1 >
terms/second/W_Window.txt
```

8.3.2 Second Term2

```
rlam  terms/second/S_extDown_V80.txt terms/second/W_extDown_V80.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_ext_allClosed.txt

rlam  terms/second/S_ext_allOpen.txt terms/second/W_ext_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_ext_allOpen.txt

rlam  terms/second/S_extDown_V80.txt terms/second/W_extDown_noblind.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_S_allClosed_W_louvers.txt

rlam  terms/second/S_extDown_V80.txt terms/second/W_extUp_V80.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_S_allClosed_W_V80half.txt

rlam  terms/second/S_extDown_noblind.txt terms/second/W_ext_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_S_louver_W_allOpen.txt

rlam  terms/second/S_extUp_V80.txt terms/second/W_ext_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_S_V80half_W_allOpen.txt

rlam  terms/second/S_extDown_noblind.txt terms/second/W_extDown_V80.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_W_allClosed_S_louvers.txt

rlam  terms/second/S_extUp_V80.txt terms/second/W_extDown_V80.txt
```

```
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_W_allClosed_S_V80half.txt

rlam  terms/second/S_ext_allOpen.txt terms/second/W_extDown_noblind.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_W_louver_S_allOpen.txt

rlam  terms/second/S_ext_allOpen.txt terms/second/W_extUp_V80.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_W_V80half_S_allOpen.txt

rlam  terms/second/S_extDown_noblind.txt
terms/second/W_extDown_noblind.txt terms/second/N_Window.txt |  rcalc -
e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_ext_louvers.txt

rlam  terms/second/S_extUp_V80.txt terms/second/W_extUp_V80.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_ext_V80half.txt

rlam  terms/second/S_extDown_V80.txt terms/second/W_ext_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_S_allClosed_W_allOpen.txt

rlam  terms/second/W_extDown_V80.txt terms/second/S_ext_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_ext_W_allClosed_S_allOpen.txt

rlam  terms/second/S_int_louver_V80.txt
terms/second/W_int_louver_V80.txt terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_int_allClosed.txt

rlam  terms/second/S_int_allOpen.txt terms/second/W_int_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_int_allOpen.txt

rlam  terms/second/S_int_louver_V80.txt
terms/second/W_int_louver_noblind.txt terms/second/N_Window.txt |
rcalc -e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_S_allClosed_W_louvers.txt

rlam  terms/second/S_int_louver_V80.txt
terms/second/W_int_retracted_V80.txt terms/second/N_Window.txt |  rcalc
-e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_S_allClosed_W_V80half.txt

rlam  terms/second/S_int_louver_noblind.txt
terms/second/W_int_allOpen.txt terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_S_louver_W_allOpen.txt

rlam  terms/second/S_int_retracted_V80.txt
terms/second/W_int_allOpen.txt terms/second/N_Window.txt |  rcalc -e
```

```
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_S_V80half_W_allOpen.txt

rlam  terms/second/S_int_louver_noblind.txt
terms/second/W_int_louver_V80.txt terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_W_allClosed_S_louvers.txt

rlam  terms/second/S_int_retracted_V80.txt
terms/second/W_int_louver_V80.txt terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_W_allClosed_S_V80half.txt

rlam  terms/second/S_int_allOpen.txt
terms/second/W_int_louver_noblind.txt terms/second/N_Window.txt |
rcalc -e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_W_louver_S_allOpen.txt

rlam  terms/second/S_int_allOpen.txt
terms/second/W_int_retracted_V80.txt terms/second/N_Window.txt |  rcalc
-e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_W_V80half_S_allOpen.txt

rlam  terms/second/S_int_louver_noblind.txt
terms/second/W_int_louver_noblind.txt terms/second/N_Window.txt |
rcalc -e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_louvers.txt

rlam  terms/second/S_int_retracted_V80.txt
terms/second/W_int_retracted_V80.txt terms/second/N_Window.txt |  rcalc
-e '$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_V80half.txt

rlam  terms/second/S_int_louver_V80.txt terms/second/W_int_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_S_allClosed_W_allOpen.txt

rlam  terms/second/W_int_louver_V80.txt terms/second/S_int_allOpen.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' >
terms/i_ds3ph_int_W_allClosed_S_allOpen.txt

rlam  terms/second/S_V80_all.txt terms/second/W_Window.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_S_V80all.txt

rlam  terms/second/S_V80_all.txt terms/second/W_V80_all.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_V80all.txt

rlam  terms/second/S_Window.txt terms/second/W_V80_all.txt
terms/second/N_Window.txt |  rcalc -e
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_W_V80all.txt

rlam  terms/second/S_Window.txt terms/second/W_Window.txt
terms/second/N_Window.txt |  rcalc -e
```

```
'$1=$1+$4+$7;$2=$2+$5+$8;$3=$3+$6+$9' > terms/i_ds3ph_Window.txt
```

8.4. Third Term

```
dctimestep -n 8760 -if matrices/directsun_ext_allClosed.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_allClosed.txt

dctimestep -n 8760 -if matrices/directsun_ext_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_allOpen.txt

dctimestep -n 8760 -if
matrices/directsun_ext_S_allClosed_W_louvers.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_S_allClosed_W_louvers.txt

dctimestep -n 8760 -if
matrices/directsun_ext_S_allClosed_W_V80half.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_S_allClosed_W_V80half.txt

dctimestep -n 8760 -if matrices/directsun_ext_S_louver_W_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_S_louver_W_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_ext_S_V80half_W_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_S_V80half_W_allOpen.txt

dctimestep -n 8760 -if
matrices/directsun_ext_W_allClosed_S_louvers.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_W_allClosed_S_louvers.txt

dctimestep -n 8760 -if
matrices/directsun_ext_W_allClosed_S_V80half.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_W_allClosed_S_V80half.txt

dctimestep -n 8760 -if matrices/directsun_ext_W_louver_S_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_W_louver_S_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_ext_W_V80half_S_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_W_V80half_S_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_ext_louvers.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_louvers.txt

dctimestep -n 8760 -if matrices/directsun_ext_V80half.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_V80half.txt

dctimestep -n 8760 -if
```

```
matrices/directsun_ext_S_allClosed_W_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_S_allClosed_W_allOpen.txt

dctimestep -n 8760 -if
matrices/directsun_ext_W_allClosed_S_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_ext_W_allClosed_S_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_int_allClosed.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_allClosed.txt

dctimestep -n 8760 -if matrices/directsun_int_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_allOpen.txt

dctimestep -n 8760 -if
matrices/directsun_int_S_allClosed_W_louvers.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_S_allClosed_W_louvers.txt

dctimestep -n 8760 -if
matrices/directsun_int_S_allClosed_W_V80half.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_S_allClosed_W_V80half.txt

dctimestep -n 8760 -if matrices/directsun_int_S_louver_W_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_S_louver_W_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_int_S_V80half_W_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_S_V80half_W_allOpen.txt

dctimestep -n 8760 -if
matrices/directsun_int_W_allClosed_S_louvers.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_W_allClosed_S_louvers.txt

dctimestep -n 8760 -if
matrices/directsun_int_W_allClosed_S_V80half.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_W_allClosed_S_V80half.txt

dctimestep -n 8760 -if matrices/directsun_int_W_louver_S_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_W_louver_S_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_int_W_V80half_S_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_W_V80half_S_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_int_V80half.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_V80half.txt
```

```
dctimestep -n 8760 -if matrices/directsun_int_louvers.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_louvers.txt

dctimestep -n 8760 -if
matrices/directsun_int_S_allClosed_W_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_S_allClosed_W_allOpen.txt

dctimestep -n 8760 -if
matrices/directsun_int_W_allClosed_S_allOpen.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_int_W_allClosed_S_allOpen.txt

dctimestep -n 8760 -if matrices/directsun_S_V80all.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_S_V80all.txt

dctimestep -n 8760 -if matrices/directsun_V80all.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_V80all.txt

dctimestep -n 8760 -if matrices/directsun_W_V80all.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_W_V80all.txt

dctimestep -n 8760 -if matrices/directsun_Window.dsmx
matrices/Milwaukee_direct_m6.smx | rcollate -h -oc 1 >
terms/i_ds5ph_Window.txt
```

8.5. Final Results Of Illuminance (Combining the Three Terms)

```
rlam terms/i_3ph_ext_allClosed.txt terms/i_ds3ph_ext_allClosed.txt
terms/i_ds5ph_ext_allClosed.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_ext_allClosed.txt

rlam terms/i_3ph_ext_allOpen.txt terms/i_ds3ph_ext_allOpen.txt
terms/i_ds5ph_ext_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_ext_allOpen.txt

rlam terms/i_3ph_ext_louvers.txt terms/i_ds3ph_ext_louvers.txt
terms/i_ds5ph_ext_louvers.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_ext_louvers.txt

rlam terms/i_3ph_ext_S_allClosed_W_louvers.txt
terms/i_ds3ph_ext_S_allClosed_W_louvers.txt
terms/i_ds5ph_ext_S_allClosed_W_louvers.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_S_allClosed_W_louvers.txt

rlam terms/i_3ph_ext_S_allClosed_W_V80half.txt
terms/i_ds3ph_ext_S_allClosed_W_V80half.txt
terms/i_ds5ph_ext_S_allClosed_W_V80half.txt | rcalc -e 'r=$1-
```

```
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_S_allClosed_W_V80half.txt

rlam terms/i_3ph_ext_S_louver_W_allOpen.txt
terms/i_ds3ph_ext_S_louver_W_allOpen.txt
terms/i_ds5ph_ext_S_louver_W_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_S_louver_W_allOpen.txt

rlam terms/i_3ph_ext_S_V80half_W_allOpen.txt
terms/i_ds3ph_ext_S_V80half_W_allOpen.txt
terms/i_ds5ph_ext_S_V80half_W_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_S_V80half_W_allOpen.txt

rlam terms/i_3ph_ext_V80half.txt terms/i_ds3ph_ext_V80half.txt
terms/i_ds5ph_ext_V80half.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_ext_V80half.txt

rlam terms/i_3ph_ext_W_allClosed_S_louvers.txt
terms/i_ds3ph_ext_W_allClosed_S_louvers.txt
terms/i_ds5ph_ext_W_allClosed_S_louvers.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_W_allClosed_S_louvers.txt

rlam terms/i_3ph_ext_W_allClosed_S_V80half.txt
terms/i_ds3ph_ext_W_allClosed_S_V80half.txt
terms/i_ds5ph_ext_W_allClosed_S_V80half.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_W_allClosed_S_V80half.txt

rlam terms/i_3ph_ext_W_louver_S_allOpen.txt
terms/i_ds3ph_ext_W_louver_S_allOpen.txt
terms/i_ds5ph_ext_W_louver_S_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_W_louver_S_allOpen.txt

rlam terms/i_3ph_ext_W_V80half_S_allOpen.txt
terms/i_ds3ph_ext_W_V80half_S_allOpen.txt
terms/i_ds5ph_ext_W_V80half_S_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_W_V80half_S_allOpen.txt

rlam terms/i_3ph_ext_S_allClosed_W_allOpen.txt
terms/i_ds3ph_ext_S_allClosed_W_allOpen.txt
terms/i_ds5ph_ext_S_allClosed_W_allOpen.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_S_allClosed_W_allOpen.txt
```

```
rlam terms/i_3ph_ext_W_allClosed_S_allOpen.txt
terms/i_ds3ph_ext_W_allClosed_S_allOpen.txt
terms/i_ds5ph_ext_W_allClosed_S_allOpen.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_ext_W_allClosed_S_allOpen.txt

rlam terms/i_3ph_int_allClosed.txt terms/i_ds3ph_int_allClosed.txt
terms/i_ds5ph_int_allClosed.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_int_allClosed.txt

rlam terms/i_3ph_int_allOpen.txt terms/i_ds3ph_int_allOpen.txt
terms/i_ds5ph_int_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_int_allOpen.txt

rlam terms/i_3ph_int_louvers.txt terms/i_ds3ph_int_louvers.txt
terms/i_ds5ph_int_louvers.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_int_louvers.txt

rlam terms/i_3ph_int_S_allClosed_W_louvers.txt
terms/i_ds3ph_int_S_allClosed_W_louvers.txt
terms/i_ds5ph_int_S_allClosed_W_louvers.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_int_S_allClosed_W_louvers.txt

rlam terms/i_3ph_int_S_allClosed_W_V80half.txt
terms/i_ds3ph_int_S_allClosed_W_V80half.txt
terms/i_ds5ph_int_S_allClosed_W_V80half.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_int_S_allClosed_W_V80half.txt

rlam terms/i_3ph_int_S_louver_W_allOpen.txt
terms/i_ds3ph_int_S_louver_W_allOpen.txt
terms/i_ds5ph_int_S_louver_W_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_int_S_louver_W_allOpen.txt

rlam terms/i_3ph_int_S_V80half_W_allOpen.txt
terms/i_ds3ph_int_S_V80half_W_allOpen.txt
terms/i_ds5ph_int_S_V80half_W_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_int_S_V80half_W_allOpen.txt

rlam terms/i_3ph_int_V80half.txt terms/i_ds3ph_int_V80half.txt
terms/i_ds5ph_int_V80half.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_int_V80half.txt

rlam terms/i_3ph_int_W_allClosed_S_louvers.txt
```

```
terms/i_ds3ph_int_W_allClosed_S_louvers.txt
terms/i_ds5ph_int_W_allClosed_S_louvers.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_int_W_allClosed_S_louvers.txt

rlam terms/i_3ph_int_W_allClosed_S_V80half.txt
terms/i_ds3ph_int_W_allClosed_S_V80half.txt
terms/i_ds5ph_int_W_allClosed_S_V80half.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_int_W_allClosed_S_V80half.txt

rlam terms/i_3ph_int_W_louver_S_allOpen.txt
terms/i_ds3ph_int_W_louver_S_allOpen.txt
terms/i_ds5ph_int_W_louver_S_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_int_W_louver_S_allOpen.txt

rlam terms/i_3ph_int_W_V80half_S_allOpen.txt
terms/i_ds3ph_int_W_V80half_S_allOpen.txt
terms/i_ds5ph_int_W_V80half_S_allOpen.txt | rcalc -e 'r=$1-$4+$7;g=$2-
$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1
-oc 8760 | rcollate -h -fa1 -t >
results/illum_int_W_V80half_S_allOpen.txt

rlam terms/i_3ph_int_S_allClosed_W_allOpen.txt
terms/i_ds3ph_int_S_allClosed_W_allOpen.txt
terms/i_ds5ph_int_S_allClosed_W_allOpen.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_int_S_allClosed_W_allOpen.txt

rlam terms/i_3ph_int_W_allClosed_S_allOpen.txt
terms/i_ds3ph_int_W_allClosed_S_allOpen.txt
terms/i_ds5ph_int_W_allClosed_S_allOpen.txt | rcalc -e 'r=$1-
$4+$7;g=$2-$5+$8;b=$3-$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' |
rcollate -h -fa1 -oc 8760 | rcollate -h -fa1 -t >
results/illum_int_W_allClosed_S_allOpen.txt

rlam terms/i_3ph_S_V80all.txt terms/i_ds3ph_S_V80all.txt
terms/i_ds5ph_S_V80all.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_S_V80all.txt

rlam terms/i_3ph_V80all.txt terms/i_ds3ph_V80all.txt
terms/i_ds5ph_V80all.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-$6+$9'
-e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_V80all.txt

rlam terms/i_3ph_W_V80all.txt terms/i_ds3ph_W_V80all.txt
terms/i_ds5ph_W_V80all.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-
$6+$9' -e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_W_V80all.txt

rlam terms/i_3ph_Window.txt terms/i_ds3ph_Window.txt
```

```
terms/i_ds5ph_Window.txt | rcalc -e 'r=$1-$4+$7;g=$2-$5+$8;b=$3-$6+$9'
-e '$1=179*(.265*r+.670*g+.065*b)' | rcollate -h -fa1 -oc 8760 |
rcollate -h -fa1 -t > results/illum_Window.txt
```

9. Rendering

9.1. View matrix

```
ulimit -n 512

vwrays -vf views/front1.vf -ff -x 500 -y 500 | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -ffc -fo -o viewpics/%s_%03d.hdr -f
klems_int.cal -bn Nkbins -b kbinS -m viewsurf_south -b kbinW -m
viewsurf_west -b kbinN -m viewsurf_north -ab 10 -ad 65536 -lw 1.52e-5
octs/model_3ph.oct

vwrays -vf views/front2.vf -ff -x 500 -y 500 | rcontrib `vwrays -vf
views/front2.vf -x 500 -y 500 -d` -ffc -fo -o viewpics2/%s_%03d.hdr -f
klems_int.cal -bn Nkbins -b kbinS -m viewsurf_south -b kbinW -m
viewsurf_west -b kbinN -m viewsurf_north -ab 10 -ad 65536 -lw 1.52e-5
octs/model_3ph.oct
```

9.2. Direct view matrix

```
vwrays -vf views/front1.vf -ff -x 500 -y 500 | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -ffc -fo -o viewpics_dir/%s_%03d.hdr
-f klems_int.cal -bn Nkbins -b kbinS -m viewsurf_south -b kbinW -m
viewsurf_west -b kbinN -m viewsurf_north -ab 1 -ad 65536 -lw 1.52e-5
octs/model_3ph.oct

vwrays -vf views/front2.vf -ff -x 500 -y 500 | rcontrib `vwrays -vf
views/front2.vf -x 500 -y 500 -d` -ffc -fo -o viewpics_dir2/%s_%03d.hdr
-f klems_int.cal -bn Nkbins -b kbinS -m viewsurf_south -b kbinW -m
viewsurf_west -b kbinN -m viewsurf_north -ab 1 -ad 65536 -lw 1.52e-5
octs/model_3ph.oct
```

9.3. Direct Sun Coefficient Matrix

9.3.1. No sun model

```
xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad >
octs/model_nosuns_Window.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_venetian80_all.rad objects/room/W_venetian80_all.rad >
octs/model_nosuns_V80all.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_venetian80_all.rad > octs/model_nosuns_S_V80all.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_allOpen.oct
```

```
xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_S_louver_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers.rad objects/room/W_venetian80_half.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_allClosed.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_S_allClosed_W_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_S_allClosed_W_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/W_ext_louvers.rad objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_W_allClosed_S_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_S_V80half_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/W_ext_louvers.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad > octs/model_nosuns_ext_V80half.oct
```

```
xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad >
octs/model_nosuns_ext_S_allClosed_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers_retracted.rad
objects/room/W_int_louvers_retracted.rad >
octs/model_nosuns_int_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/W_int_louvers_retracted.rad
> octs/model_nosuns_int_S_louver_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers.rad objects/room/W_venetian80_half.rad >
octs/model_nosuns_int_allClosed.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/room/W_venetian80_half.rad >
octs/model_nosuns_int_S_allClosed_W_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers.rad >
octs/model_nosuns_int_S_allClosed_W_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad >
octs/model_nosuns_int_S_V80half_W_allOpen.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/room/W_venetian80_half.rad > octs/model_nosuns_int_V80half.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/W_int_louvers.rad >
octs/model_nosuns_int_louvers.oct

xform -m black objects/room/room.rad objects/ground.rad | oconv
```

```
materials/AUP406.mat - objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad >
octs/model_nosuns_int_S_allClosed_W_allOpen.oct
```

9.3.2. Direct Sun Matrix

```
ulimit -n 9999

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_allClosed.oct | rcontrib `vwrays -
vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/exterior2_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_allClosed.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_allOpen.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/exterior1_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_allOpen.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_louvers.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/exterior13_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_louvers.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_S_allClosed_W_allOpen.oct |
rcontrib `vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -
o viewpics_ds/exterior3_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_S_allClosed_W_allOpen.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_S_allClosed_W_louvers.oct |
rcontrib `vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -
o viewpics_ds/exterior4_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_S_allClosed_W_louvers.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_S_allClosed_W_V80half.oct |
rcontrib `vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -
o viewpics_ds/exterior5_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_S_allClosed_W_V80half.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_S_louver_W_allOpen.oct | rcontrib
`vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/exterior11_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_S_louver_W_allOpen.oct
```

```
vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_S_V80half_W_allOpen.oct | rcontrib
`vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/exterior12_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_S_V80half_W_allOpen.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_V80half.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/exterior14_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_V80half.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_ext_W_allClosed_S_louvers.oct |
rcontrib `vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -
o viewpics_ds/exterior9_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_ext_W_allClosed_S_louvers.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_allClosed.oct | rcontrib `vwrays -
vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/interior2_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_allClosed.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_S_allClosed_W_V80half.oct |
rcontrib `vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -
o viewpics_ds/interior5_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_S_allClosed_W_V80half.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_S_louver_W_allOpen.oct | rcontrib
`vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/interior11_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_S_louver_W_allOpen.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_S_V80half_W_allOpen.oct | rcontrib
`vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/interior12_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_S_V80half_W_allOpen.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_V80half.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/interior14_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_V80half.oct
```

```
vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_S_V80all.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/existing3_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_S_V80all.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_V80all.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/existing2_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_V80all.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_Window.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/existing1_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_Window.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_allOpen.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/interior1_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_allOpen.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_louvers.oct | rcontrib `vwrays -vf
views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -o
viewpics_ds/interior13_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_louvers.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_S_allClosed_W_allOpen.oct |
rcontrib `vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -
o viewpics_ds/interior3_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_S_allClosed_W_allOpen.oct

vwrays -c 4 -pj 1 -fa -vf views/front1.vf -x 500 -y 500 | rtrace -h- -
opn -faa -ab 0 octs/model_nosuns_int_S_allClosed_W_louvers.oct |
rcontrib `vwrays -vf views/front1.vf -x 500 -y 500 -d` -n 32 -fac -fo -
o viewpics_ds/interior4_%04d.hdr -e MF:6 -f reinhart.cal -b rbin -bn
Nrbins -m solar -c 4 -I -ab 1 -ad 100 -dt 0 -dc 1 -lw 1e-2
octs/model_suns_int_S_allClosed_W_louvers.oct
```

9.4. Material map

9.4.1. Material map model

```
oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
```

```
octs/model_material_Window.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_venetian80_all.rad objects/room/W_venetian80_all.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_V80all.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_venetian80_all.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_S_V80all.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_allOpen.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_S_louver_W_allOpen.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers.rad objects/room/W_venetian80_half.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_allClosed.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_S_allClosed_W_V80half.oct
```

```
oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_S_allClosed_W_louvers.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/W_ext_louvers.rad objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_W_allClosed_S_louvers.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_S_V80half_W_allOpen.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/W_ext_louvers.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_louvers.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad
objects/room/S_ext_louvers_retracted.rad
objects/room/W_venetian80_half.rad objects/room/W_lightshelves.rad
objects/room/S_lightshelves.rad objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_ext_V80half.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_ext_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_ext_louvers_retracted.rad
objects/room/W_lightshelves.rad objects/room/S_lightshelves.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
```

```
octs/model_material_ext_S_allClosed_W_allOpen.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers_retracted.rad
objects/room/W_int_louvers_retracted.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_allOpen.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/W_int_louvers_retracted.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_S_louver_W_allOpen.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers.rad objects/room/W_venetian80_half.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_allClosed.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/room/W_venetian80_half.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_S_allClosed_W_V80half.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers.rad objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_S_allClosed_W_louvers.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_S_V80half_W_allOpen.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
```

```
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers_retracted.rad
objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/room/W_venetian80_half.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_V80half.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/W_int_louvers.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_louvers.oct

oconv materials/AUP406.mat objects/room/room.rad objects/ground.rad
objects/room/glazing.rad objects/room/windowFrame.rad
objects/room/S_int_louvers.rad objects/room/S_venetian80_half.rad
objects/room/W_int_louvers_retracted.rad
objects/daymtxsurf/daymtxsurf_south.rad
objects/daymtxsurf/daymtxsurf_west.rad
objects/daymtxsurf/daymtxsurf_north.rad >
octs/model_material_int_S_allClosed_W_allOpen.oct
```

9.4.2. Material map image

```
rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_allClosed.oct | pfilt -x
/2 -y /2 -1 -e 1 > materialMap/front1/ext_allClosed.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_allOpen.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front1/ext_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_louvers.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front1/ext_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_allClosed_W_allOpen.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/ext_S_allClosed_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_allClosed_W_louvers.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/ext_S_allClosed_W_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_allClosed_W_V80half.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/ext_S_allClosed_W_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
```

```
0.31831 0.31831 -aa 0 octs/model_material_ext_S_louver_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/ext_S_louver_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_V80half_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/ext_S_V80half_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_V80half.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front1/ext_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_W_allClosed_S_louvers.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/ext_W_allClosed_S_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_allClosed.oct | pfilt -x
/2 -y /2 -1 -e 1 > materialMap/front1/int_allClosed.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_allOpen.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front1/int_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_louvers.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front1/int_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_allClosed_W_allOpen.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/int_S_allClosed_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_allClosed_W_louvers.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/int_S_allClosed_W_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_allClosed_W_V80half.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/int_S_allClosed_W_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_louver_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/int_S_louver_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_V80half_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front1/int_S_V80half_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_V80half.oct | pfilt -x /2
```

```
-y /2 -1 -e 1 > materialMap/front1/int_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_S_V80all.oct | pfilt -x /2 -y
/2 -1 -e 1 > materialMap/front1/S_V80all.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_V80all.oct | pfilt -x /2 -y
/2 -1 -e 1 > materialMap/front1/V80all.hdr

rpict -x 1000 -y 1000 -vf views/front1.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_Window.oct | pfilt -x /2 -y
/2 -1 -e 1 > materialMap/front1/Window.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_allClosed.oct | pfilt -x
/2 -y /2 -1 -e 1 > materialMap/front2/ext_allClosed.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_allOpen.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front2/ext_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_louvers.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front2/ext_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_allClosed_W_allOpen.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/ext_S_allClosed_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_allClosed_W_louvers.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/ext_S_allClosed_W_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_allClosed_W_V80half.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/ext_S_allClosed_W_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_louver_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/ext_S_louver_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_S_V80half_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/ext_S_V80half_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_V80half.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front2/ext_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_ext_W_allClosed_S_louvers.oct
```

```
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/ext_W_allClosed_S_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_allClosed.oct | pfilt -x
/2 -y /2 -1 -e 1 > materialMap/front2/int_allClosed.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_allOpen.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front2/int_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_louvers.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front2/int_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_allClosed_W_allOpen.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/int_S_allClosed_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_allClosed_W_louvers.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/int_S_allClosed_W_louvers.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_allClosed_W_V80half.oct
| pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/int_S_allClosed_W_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_louver_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/int_S_louver_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_S_V80half_W_allOpen.oct |
pfilt -x /2 -y /2 -1 -e 1 >
materialMap/front2/int_S_V80half_W_allOpen.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_int_V80half.oct | pfilt -x /2
-y /2 -1 -e 1 > materialMap/front2/int_V80half.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_S_V80all.oct | pfilt -x /2 -y
/2 -1 -e 1 > materialMap/front2/S_V80all.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_V80all.oct | pfilt -x /2 -y
/2 -1 -e 1 > materialMap/front2/V80all.hdr

rpict -x 1000 -y 1000 -vf views/front2.vf -ps 1 -pj 1 -av 0.31831
0.31831 0.31831 -aa 0 octs/model_material_Window.oct | pfilt -x /2 -y
/2 -1 -e 1 > materialMap/front2/Window.hdr
```

9.5. Putting it all together
9.5.1. Weather files

Interior and exterior
1=all open
2=all closed
3= S all closed, W all open
4= S all closed, W louver only
5= S all closed, W V80 only
9= W all closed, S louver only
11= W all open, S louver only
12= W all open, S V80 only
13=louvers
14=V80 half
Existing
1=all open
2=all closed
3= S V80, W open

The control algorithm excel file was sorted based on the control number, then corresponding weather data was copied into a textfile named xxxx.wea.

```
gendaymtx -of WEA/existing1.wea > skies/existing1.smx
gendaymtx -of -d WEA/existing1.wea > skies/existing1_direct.smx
gendaymtx -5 -d -m 6 -of WEA/existing1.wea >
skies/existing1_direct_m6.smx

gendaymtx -of WEA/existing2.wea > skies/existing2.smx
gendaymtx -of -d WEA/existing2.wea > skies/existing2_direct.smx
gendaymtx -5 -d -m 6 -of WEA/existing2.wea >
skies/existing2_direct_m6.smx

gendaymtx -of WEA/existing3.wea > skies/existing3.smx
gendaymtx -of -d WEA/existing3.wea > skies/existing3_direct.smx
gendaymtx -5 -d -m 6 -of WEA/existing3.wea >
skies/existing3_direct_m6.smx

gendaymtx -of WEA/interior1.wea > skies/interior1.smx
gendaymtx -of -d WEA/interior1.wea > skies/interior1_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior1.wea >
skies/interior1_direct_m6.smx

gendaymtx -of WEA/interior2.wea > skies/interior2.smx
gendaymtx -of -d WEA/interior2.wea > skies/interior2_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior2.wea >
skies/interior2_direct_m6.smx

gendaymtx -of WEA/interior3.wea > skies/interior3.smx
gendaymtx -of -d WEA/interior3.wea > skies/interior3_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior3.wea >
skies/interior3_direct_m6.smx

gendaymtx -of WEA/interior4.wea > skies/interior4.smx
gendaymtx -of -d WEA/interior4.wea > skies/interior4_direct.smx
```

```
gendaymtx -5 -d -m 6 -of WEA/interior4.wea >
skies/interior4_direct_m6.smx

gendaymtx -of WEA/interior5.wea > skies/interior5.smx
gendaymtx -of -d WEA/interior5.wea > skies/interior5_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior5.wea >
skies/interior5_direct_m6.smx

gendaymtx -of WEA/interior11.wea > skies/interior11.smx
gendaymtx -of -d WEA/interior11.wea > skies/interior11_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior11.wea >
skies/interior11_direct_m6.smx

gendaymtx -of WEA/interior12.wea > skies/interior12.smx
gendaymtx -of -d WEA/interior12.wea > skies/interior12_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior12.wea >
skies/interior12_direct_m6.smx

gendaymtx -of WEA/interior13.wea > skies/interior13.smx
gendaymtx -of -d WEA/interior13.wea > skies/interior13_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior13.wea >
skies/interior13_direct_m6.smx

gendaymtx -of WEA/interior14.wea > skies/interior14.smx
gendaymtx -of -d WEA/interior14.wea > skies/interior14_direct.smx
gendaymtx -5 -d -m 6 -of WEA/interior14.wea >
skies/interior14_direct_m6.smx

gendaymtx -of WEA/exterior1.wea > skies/exterior1.smx
gendaymtx -of -d WEA/exterior1.wea > skies/exterior1_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior1.wea >
skies/exterior1_direct_m6.smx

gendaymtx -of WEA/exterior2.wea > skies/exterior2.smx
gendaymtx -of -d WEA/exterior2.wea > skies/exterior2_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior2.wea >
skies/exterior2_direct_m6.smx

gendaymtx -of WEA/exterior3.wea > skies/exterior3.smx
gendaymtx -of -d WEA/exterior3.wea > skies/exterior3_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior3.wea >
skies/exterior3_direct_m6.smx

gendaymtx -of WEA/exterior4.wea > skies/exterior4.smx
gendaymtx -of -d WEA/exterior4.wea > skies/exterior4_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior4.wea >
skies/exterior4_direct_m6.smx

gendaymtx -of WEA/exterior5.wea > skies/exterior5.smx
gendaymtx -of -d WEA/exterior5.wea > skies/exterior5_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior5.wea >
skies/exterior5_direct_m6.smx

gendaymtx -of WEA/exterior9.wea > skies/exterior9.smx
gendaymtx -of -d WEA/exterior9.wea > skies/exterior9_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior9.wea >
skies/exterior9_direct_m6.smx
```

```
gendaymtx -of WEA/exterior11.wea > skies/exterior11.smx
gendaymtx -of -d WEA/exterior11.wea > skies/exterior11_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior11.wea >
skies/exterior11_direct_m6.smx

gendaymtx -of WEA/exterior12.wea > skies/exterior12.smx
gendaymtx -of -d WEA/exterior12.wea > skies/exterior12_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior12.wea >
skies/exterior12_direct_m6.smx

gendaymtx -of WEA/exterior13.wea > skies/exterior13.smx
gendaymtx -of -d WEA/exterior13.wea > skies/exterior13_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior13.wea >
skies/exterior13_direct_m6.smx

gendaymtx -of WEA/exterior14.wea > skies/exterior14.smx
gendaymtx -of -d WEA/exterior14.wea > skies/exterior14_direct.smx
gendaymtx -5 -d -m 6 -of WEA/exterior14.wea >
skies/exterior14_direct_m6.smx
```

9.5.2. Render-First term

9.5.2.1. First term

```
dctimestep -n 767 -if -o hourlypics/front1/S_interior1_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_south.dmx skies/interior1.smx

dctimestep -n 767 -if -o hourlypics/front1/W_interior1_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/interior1.smx

dctimestep -n 767 -if -o hourlypics/front1/N_interior1_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior1.smx

dctimestep -n 1691 -if -o hourlypics/front1/S_interior2_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/interior2.smx

dctimestep -n 1691 -if -o hourlypics/front1/W_interior2_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_west.dmx skies/interior2.smx

dctimestep -n 1691 -if -o hourlypics/front1/N_interior2_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior2.smx

dctimestep -n 356 -if -o hourlypics/front1/S_interior3_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/interior3.smx

dctimestep -n 356 -if -o hourlypics/front1/W_interior3_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/interior3.smx

dctimestep -n 356 -if -o hourlypics/front1/N_interior3_%04d.hdr
```

```
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior3.smx

dctimestep -n 147 -if -o hourlypics/front1/S_interior4_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/interior4.smx

dctimestep -n 147 -if -o hourlypics/front1/W_interior4_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_west.dmx skies/interior4.smx

dctimestep -n 147 -if -o hourlypics/front1/N_interior4_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior4.smx

dctimestep -n 298 -if -o hourlypics/front1/S_interior5_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/interior5.smx

dctimestep -n 298 -if -o hourlypics/front1/W_interior5_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_west.dmx skies/interior5.smx

dctimestep -n 298 -if -o hourlypics/front1/N_interior5_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior5.smx

dctimestep -n 708 -if -o hourlypics/front1/S_interior11_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_south.dmx skies/interior11.smx

dctimestep -n 708 -if -o hourlypics/front1/W_interior11_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/interior11.smx

dctimestep -n 708 -if -o hourlypics/front1/N_interior11_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior11.smx

dctimestep -n 46 -if -o hourlypics/front1/S_interior12_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/interior12.smx

dctimestep -n 46 -if -o hourlypics/front1/W_interior12_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/interior12.smx

dctimestep -n 46 -if -o hourlypics/front1/N_interior12_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior12.smx

dctimestep -n 15 -if -o hourlypics/front1/S_interior13_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_south.dmx skies/interior13.smx

dctimestep -n 15 -if -o hourlypics/front1/W_interior13_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_louver_noblind_klems.xml
```

```
matrices/daylightmatrix_west.dmx skies/interior13.smx

dctimestep -n 15 -if -o hourlypics/front1/N_interior13_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior13.smx

dctimestep -n 663 -if -o hourlypics/front1/S_interior14_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/interior14.smx

dctimestep -n 663 -if -o hourlypics/front1/W_interior14_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_west.dmx skies/interior14.smx

dctimestep -n 663 -if -o hourlypics/front1/N_interior14_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/interior14.smx

dctimestep -n 977 -if -o hourlypics/front1/S_exterior1_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_ext_allOpen_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior1.smx

dctimestep -n 977 -if -o hourlypics/front1/W_exterior1_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior1.smx

dctimestep -n 977 -if -o hourlypics/front1/N_exterior1_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior1.smx

dctimestep -n 1212 -if -o hourlypics/front1/S_exterior2_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior2.smx

dctimestep -n 1212 -if -o hourlypics/front1/W_exterior2_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_extDown_V80_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior2.smx

dctimestep -n 1212 -if -o hourlypics/front1/N_exterior2_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior2.smx

dctimestep -n 483 -if -o hourlypics/front1/S_exterior3_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior3.smx

dctimestep -n 483 -if -o hourlypics/front1/W_exterior3_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior3.smx

dctimestep -n 483 -if -o hourlypics/front1/N_exterior3_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior3.smx

dctimestep -n 593 -if -o hourlypics/front1/S_exterior4_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior4.smx
```

```
dctimestep -n 593 -if -o hourlypics/front1/W_exterior4_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_extDown_noblind_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior4.smx

dctimestep -n 593 -if -o hourlypics/front1/N_exterior4_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior4.smx

dctimestep -n 40 -if -o hourlypics/front1/S_exterior5_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior5.smx

dctimestep -n 40 -if -o hourlypics/front1/W_exterior5_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_extUp_V80_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior5.smx

dctimestep -n 40 -if -o hourlypics/front1/N_exterior5_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior5.smx

dctimestep -n 5 -if -o hourlypics/front1/S_exterior9_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extDown_noblind_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior9.smx

dctimestep -n 5 -if -o hourlypics/front1/W_exterior9_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_extDown_V80_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior9.smx

dctimestep -n 5 -if -o hourlypics/front1/N_exterior9_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior9.smx

dctimestep -n 839 -if -o hourlypics/front1/S_exterior11_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extDown_noblind_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior11.smx

dctimestep -n 839 -if -o hourlypics/front1/W_exterior11_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior11.smx

dctimestep -n 839 -if -o hourlypics/front1/N_exterior11_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior11.smx

dctimestep -n 318 -if -o hourlypics/front1/S_exterior12_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extUp_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior12.smx

dctimestep -n 318 -if -o hourlypics/front1/W_exterior12_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior12.smx

dctimestep -n 318 -if -o hourlypics/front1/N_exterior12_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior12.smx
```

```
dctimestep -n 43 -if -o hourlypics/front1/S_exterior13_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extDown_noblind_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior13.smx

dctimestep -n 43 -if -o hourlypics/front1/W_exterior13_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_extDown_noblind_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior13.smx

dctimestep -n 43 -if -o hourlypics/front1/N_exterior13_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior13.smx

dctimestep -n 181 -if -o hourlypics/front1/S_exterior14_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/S_extUp_V80_klems.xml
matrices/daylightmatrix_south.dmx skies/exterior14.smx

dctimestep -n 181 -if -o hourlypics/front1/W_exterior14_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/W_extUp_V80_klems.xml
matrices/daylightmatrix_west.dmx skies/exterior14.smx

dctimestep -n 181 -if -o hourlypics/front1/N_exterior14_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/exterior14.smx

dctimestep -n 1490 -if -o hourlypics/front1/S_existing1_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_south.dmx skies/existing1.smx

dctimestep -n 1490 -if -o hourlypics/front1/W_existing1_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_west.dmx skies/existing1.smx

dctimestep -n 1490 -if -o hourlypics/front1/N_existing1_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/existing1.smx

dctimestep -n 2652 -if -o hourlypics/front1/S_existing2_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/V80_all_klems.xml
matrices/daylightmatrix_south.dmx skies/existing2.smx

dctimestep -n 2652 -if -o hourlypics/front1/W_existing2_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/V80_all_klems.xml
matrices/daylightmatrix_west.dmx skies/existing2.smx

dctimestep -n 2652 -if -o hourlypics/front1/N_existing2_%04d.hdr
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/existing2.smx  ;

dctimestep -n 549 -if -o hourlypics/front1/S_existing3_%04d.hdr
viewpics/viewsurf_south_%03d.hdr bsdf/V80_all_klems.xml
matrices/daylightmatrix_south.dmx skies/existing3.smx

dctimestep -n 549 -if -o hourlypics/front1/W_existing3_%04d.hdr
viewpics/viewsurf_west_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_west.dmx skies/existing3.smx

dctimestep -n 549 -if -o hourlypics/front1/N_existing3_%04d.hdr
```

```
viewpics/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_north.dmx skies/existing3.smx;
```

9.5.2.2. Combing the three orientations

```
$ cd bashfiles
$ chmod +x render_first.sh
$ ./render_first.sh

#render_first.sh:
#!/bin/bash

for t in {1..767}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior1_${ts}.hdr -o
hourlypics/front1/W_interior1_${ts}.hdr -o
hourlypics/front1/N_interior1_${ts}.hdr >
hourlypics/front1/interior1_${ts}.hdr
done

for t in {1..1691}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior2_${ts}.hdr -o
hourlypics/front1/W_interior2_${ts}.hdr -o
hourlypics/front1/N_interior2_${ts}.hdr >
hourlypics/front1/interior2_${ts}.hdr
done

for t in {1..356}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior3_${ts}.hdr -o
hourlypics/front1/W_interior3_${ts}.hdr -o
hourlypics/front1/N_interior3_${ts}.hdr >
hourlypics/front1/interior3_${ts}.hdr
done

for t in {1..147}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior4_${ts}.hdr -o
hourlypics/front1/W_interior4_${ts}.hdr -o
hourlypics/front1/N_interior4_${ts}.hdr >
hourlypics/front1/interior4_${ts}.hdr
done

for t in {1..298}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior5_${ts}.hdr -o
hourlypics/front1/W_interior5_${ts}.hdr -o
hourlypics/front1/N_interior5_${ts}.hdr >
hourlypics/front1/interior5_${ts}.hdr
done
```

```
for t in {1..708}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior11_${ts}.hdr -o
hourlypics/front1/W_interior11_${ts}.hdr -o
hourlypics/front1/N_interior11_${ts}.hdr >
hourlypics/front1/interior11_${ts}.hdr
done

for t in {1..46}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior12_${ts}.hdr -o
hourlypics/front1/W_interior12_${ts}.hdr -o
hourlypics/front1/N_interior12_${ts}.hdr >
hourlypics/front1/interior12_${ts}.hdr
done

for t in {1..15}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior13_${ts}.hdr -o
hourlypics/front1/W_interior13_${ts}.hdr -o
hourlypics/front1/N_interior13_${ts}.hdr >
hourlypics/front1/interior13_${ts}.hdr
done

for t in {1..663}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_interior14_${ts}.hdr -o
hourlypics/front1/W_interior14_${ts}.hdr -o
hourlypics/front1/N_interior14_${ts}.hdr >
hourlypics/front1/interior14_${ts}.hdr
done

for t in {1..977}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior1_${ts}.hdr -o
hourlypics/front1/W_exterior1_${ts}.hdr -o
hourlypics/front1/N_exterior1_${ts}.hdr >
hourlypics/front1/exterior1_${ts}.hdr
done

for t in {1..1212}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior2_${ts}.hdr -o
hourlypics/front1/W_exterior2_${ts}.hdr -o
hourlypics/front1/N_exterior2_${ts}.hdr >
hourlypics/front1/exterior2_${ts}.hdr
done

for t in {1..483}
do ts=`printf %04d $t `
```

```
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior3_${ts}.hdr -o
hourlypics/front1/W_exterior3_${ts}.hdr -o
hourlypics/front1/N_exterior3_${ts}.hdr >
hourlypics/front1/exterior3_${ts}.hdr
done

for t in {1..593}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior4_${ts}.hdr -o
hourlypics/front1/W_exterior4_${ts}.hdr -o
hourlypics/front1/N_exterior4_${ts}.hdr >
hourlypics/front1/exterior4_${ts}.hdr
done

for t in {1..40}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior5_${ts}.hdr -o
hourlypics/front1/W_exterior5_${ts}.hdr -o
hourlypics/front1/N_exterior5_${ts}.hdr >
hourlypics/front1/exterior5_${ts}.hdr
done

for t in {1..5}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior9_${ts}.hdr -o
hourlypics/front1/W_exterior9_${ts}.hdr -o
hourlypics/front1/N_exterior9_${ts}.hdr >
hourlypics/front1/exterior9_${ts}.hdr
done

for t in {1..839}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior11_${ts}.hdr -o
hourlypics/front1/W_exterior11_${ts}.hdr -o
hourlypics/front1/N_exterior11_${ts}.hdr >
hourlypics/front1/exterior11_${ts}.hdr
done

for t in {1..318}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior12_${ts}.hdr -o
hourlypics/front1/W_exterior12_${ts}.hdr -o
hourlypics/front1/N_exterior12_${ts}.hdr >
hourlypics/front1/exterior12_${ts}.hdr
done

for t in {1..43}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior13_${ts}.hdr -o
hourlypics/front1/W_exterior13_${ts}.hdr -o
```

```
hourlypics/front1/N_exterior13_${ts}.hdr >
hourlypics/front1/exterior13_${ts}.hdr
done

for t in {1..181}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_exterior14_${ts}.hdr -o
hourlypics/front1/W_exterior14_${ts}.hdr -o
hourlypics/front1/N_exterior14_${ts}.hdr >
hourlypics/front1/exterior14_${ts}.hdr
done

for t in {1..1490}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_existing1_${ts}.hdr -o
hourlypics/front1/W_existing1_${ts}.hdr -o
hourlypics/front1/N_existing1_${ts}.hdr >
hourlypics/front1/existing1_${ts}.hdr
done

for t in {1..2652}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_existing2_${ts}.hdr -o
hourlypics/front1/W_existing2_${ts}.hdr -o
hourlypics/front1/N_existing2_${ts}.hdr >
hourlypics/front1/existing2_${ts}.hdr
done

for t in {1..549}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front1/S_existing3_${ts}.hdr -o
hourlypics/front1/W_existing3_${ts}.hdr -o
hourlypics/front1/N_existing3_${ts}.hdr >
hourlypics/front1/existing3_${ts}.hdr
done

for t in {1..767}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior1_${ts}.hdr -o
hourlypics/front2/W_interior1_${ts}.hdr -o
hourlypics/front2/N_interior1_${ts}.hdr >
hourlypics/front2/interior1_${ts}.hdr
done

for t in {1..1691}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior2_${ts}.hdr -o
hourlypics/front2/W_interior2_${ts}.hdr -o
hourlypics/front2/N_interior2_${ts}.hdr >
hourlypics/front2/interior2_${ts}.hdr
done
```

```
for t in {1..356}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior3_${ts}.hdr -o
hourlypics/front2/W_interior3_${ts}.hdr -o
hourlypics/front2/N_interior3_${ts}.hdr >
hourlypics/front2/interior3_${ts}.hdr
done

for t in {1..147}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior4_${ts}.hdr -o
hourlypics/front2/W_interior4_${ts}.hdr -o
hourlypics/front2/N_interior4_${ts}.hdr >
hourlypics/front2/interior4_${ts}.hdr
done

for t in {1..298}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior5_${ts}.hdr -o
hourlypics/front2/W_interior5_${ts}.hdr -o
hourlypics/front2/N_interior5_${ts}.hdr >
hourlypics/front2/interior5_${ts}.hdr
done

for t in {1..708}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior11_${ts}.hdr -o
hourlypics/front2/W_interior11_${ts}.hdr -o
hourlypics/front2/N_interior11_${ts}.hdr >
hourlypics/front2/interior11_${ts}.hdr
done

for t in {1..46}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior12_${ts}.hdr -o
hourlypics/front2/W_interior12_${ts}.hdr -o
hourlypics/front2/N_interior12_${ts}.hdr >
hourlypics/front2/interior12_${ts}.hdr
done

for t in {1..15}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior13_${ts}.hdr -o
hourlypics/front2/W_interior13_${ts}.hdr -o
hourlypics/front2/N_interior13_${ts}.hdr >
hourlypics/front2/interior13_${ts}.hdr
done

for t in {1..663}
do ts=`printf %04d $t `
```

```
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_interior14_${ts}.hdr -o
hourlypics/front2/W_interior14_${ts}.hdr -o
hourlypics/front2/N_interior14_${ts}.hdr >
hourlypics/front2/interior14_${ts}.hdr
done

for t in {1..977}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior1_${ts}.hdr -o
hourlypics/front2/W_exterior1_${ts}.hdr -o
hourlypics/front2/N_exterior1_${ts}.hdr >
hourlypics/front2/exterior1_${ts}.hdr
done

for t in {1..1212}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior2_${ts}.hdr -o
hourlypics/front2/W_exterior2_${ts}.hdr -o
hourlypics/front2/N_exterior2_${ts}.hdr >
hourlypics/front2/exterior2_${ts}.hdr
done

for t in {1..483}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior3_${ts}.hdr -o
hourlypics/front2/W_exterior3_${ts}.hdr -o
hourlypics/front2/N_exterior3_${ts}.hdr >
hourlypics/front2/exterior3_${ts}.hdr
done

for t in {1..593}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior4_${ts}.hdr -o
hourlypics/front2/W_exterior4_${ts}.hdr -o
hourlypics/front2/N_exterior4_${ts}.hdr >
hourlypics/front2/exterior4_${ts}.hdr
done

for t in {1..40}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior5_${ts}.hdr -o
hourlypics/front2/W_exterior5_${ts}.hdr -o
hourlypics/front2/N_exterior5_${ts}.hdr >
hourlypics/front2/exterior5_${ts}.hdr
done

for t in {1..5}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior9_${ts}.hdr -o
hourlypics/front2/W_exterior9_${ts}.hdr -o
```

```
hourlypics/front2/N_exterior9_${ts}.hdr >
hourlypics/front2/exterior9_${ts}.hdr
done

for t in {1..839}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior11_${ts}.hdr -o
hourlypics/front2/W_exterior11_${ts}.hdr -o
hourlypics/front2/N_exterior11_${ts}.hdr >
hourlypics/front2/exterior11_${ts}.hdr
done

for t in {1..318}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior12_${ts}.hdr -o
hourlypics/front2/W_exterior12_${ts}.hdr -o
hourlypics/front2/N_exterior12_${ts}.hdr >
hourlypics/front2/exterior12_${ts}.hdr
done

for t in {1..43}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior13_${ts}.hdr -o
hourlypics/front2/W_exterior13_${ts}.hdr -o
hourlypics/front2/N_exterior13_${ts}.hdr >
hourlypics/front2/exterior13_${ts}.hdr
done

for t in {1..181}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_exterior14_${ts}.hdr -o
hourlypics/front2/W_exterior14_${ts}.hdr -o
hourlypics/front2/N_exterior14_${ts}.hdr >
hourlypics/front2/exterior14_${ts}.hdr
done

for t in {1..1490}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_existing1_${ts}.hdr -o
hourlypics/front2/W_existing1_${ts}.hdr -o
hourlypics/front2/N_existing1_${ts}.hdr >
hourlypics/front2/existing1_${ts}.hdr
done

for t in {1..2652}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_existing2_${ts}.hdr -o
hourlypics/front2/W_existing2_${ts}.hdr -o
hourlypics/front2/N_existing2_${ts}.hdr >
hourlypics/front2/existing2_${ts}.hdr
done
```

```
for t in {1..549}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics/front2/S_existing3_${ts}.hdr -o
hourlypics/front2/W_existing3_${ts}.hdr -o
hourlypics/front2/N_existing3_${ts}.hdr >
hourlypics/front2/existing3_${ts}.hdr
done
```

9.5.3. Render-second term

9.5.3.1 Second term

```
dctimestep -n 767 -if -o hourlypics_dir/front1/S_interior1_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior1_direct.smx

dctimestep -n 767 -if -o hourlypics_dir/front1/W_interior1_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior1_direct.smx

dctimestep -n 767 -if -o hourlypics_dir/front1/N_interior1_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior1_direct.smx

dctimestep -n 1691 -if -o hourlypics_dir/front1/S_interior2_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior2_direct.smx

dctimestep -n 1691 -if -o hourlypics_dir/front1/W_interior2_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior2_direct.smx

dctimestep -n 1691 -if -o hourlypics_dir/front1/N_interior2_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior2_direct.smx

dctimestep -n 356 -if -o hourlypics_dir/front1/S_interior3_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior3_direct.smx

dctimestep -n 356 -if -o hourlypics_dir/front1/W_interior3_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior3_direct.smx

dctimestep -n 356 -if -o hourlypics_dir/front1/N_interior3_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior3_direct.smx

dctimestep -n 147 -if -o hourlypics_dir/front1/S_interior4_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior4_direct.smx

dctimestep -n 147 -if -o hourlypics_dir/front1/W_interior4_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior4_direct.smx
```

```
dctimestep -n 147 -if -o hourlypics_dir/front1/N_interior4_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior4_direct.smx

dctimestep -n 298 -if -o hourlypics_dir/front1/S_interior5_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_louver_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior5_direct.smx

dctimestep -n 298 -if -o hourlypics_dir/front1/W_interior5_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior5_direct.smx

dctimestep -n 298 -if -o hourlypics_dir/front1/N_interior5_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior5_direct.smx

dctimestep -n 708 -if -o hourlypics_dir/front1/S_interior11_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior11_direct.smx

dctimestep -n 708 -if -o hourlypics_dir/front1/W_interior11_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior11_direct.smx

dctimestep -n 708 -if -o hourlypics_dir/front1/N_interior11_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior11_direct.smx

dctimestep -n 46 -if -o hourlypics_dir/front1/S_interior12_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior12_direct.smx

dctimestep -n 46 -if -o hourlypics_dir/front1/W_interior12_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior12_direct.smx

dctimestep -n 46 -if -o hourlypics_dir/front1/N_interior12_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior12_direct.smx

dctimestep -n 15 -if -o hourlypics_dir/front1/S_interior13_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior13_direct.smx

dctimestep -n 15 -if -o hourlypics_dir/front1/W_interior13_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_louver_noblind_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior13_direct.smx

dctimestep -n 15 -if -o hourlypics_dir/front1/N_interior13_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior13_direct.smx

dctimestep -n 663 -if -o hourlypics_dir/front1/S_interior14_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/interior14_direct.smx
```

```
dctimestep -n 663 -if -o hourlypics_dir/front1/W_interior14_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/int_retracted_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/interior14_direct.smx

dctimestep -n 663 -if -o hourlypics_dir/front1/N_interior14_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/interior14_direct.smx

dctimestep -n 977 -if -o hourlypics_dir/front1/S_exterior1_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_ext_allOpen_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior1_direct.smx

dctimestep -n 977 -if -o hourlypics_dir/front1/W_exterior1_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior1_direct.smx

dctimestep -n 977 -if -o hourlypics_dir/front1/N_exterior1_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior1_direct.smx

dctimestep -n 1212 -if -o hourlypics_dir/front1/S_exterior2_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior2_direct.smx

dctimestep -n 1212 -if -o hourlypics_dir/front1/W_exterior2_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_extDown_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior2_direct.smx

dctimestep -n 1212 -if -o hourlypics_dir/front1/N_exterior2_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior2_direct.smx

dctimestep -n 483 -if -o hourlypics_dir/front1/S_exterior3_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior3_direct.smx

dctimestep -n 483 -if -o hourlypics_dir/front1/W_exterior3_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior3_direct.smx

dctimestep -n 483 -if -o hourlypics_dir/front1/N_exterior3_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior3_direct.smx

dctimestep -n 593 -if -o hourlypics_dir/front1/S_exterior4_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior4_direct.smx

dctimestep -n 593 -if -o hourlypics_dir/front1/W_exterior4_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_extDown_noblind_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior4_direct.smx

dctimestep -n 593 -if -o hourlypics_dir/front1/N_exterior4_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior4_direct.smx

dctimestep -n 40 -if -o hourlypics_dir/front1/S_exterior5_%04d.hdr
```

```
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extDown_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior5_direct.smx

dctimestep -n 40 -if -o hourlypics_dir/front1/W_exterior5_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_extUp_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior5_direct.smx

dctimestep -n 40 -if -o hourlypics_dir/front1/N_exterior5_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior5_direct.smx

dctimestep -n 5 -if -o hourlypics_dir/front1/S_exterior9_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extDown_noblind_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior9_direct.smx

dctimestep -n 5 -if -o hourlypics_dir/front1/W_exterior9_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_extDown_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior9_direct.smx

dctimestep -n 5 -if -o hourlypics_dir/front1/N_exterior9_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior9_direct.smx

dctimestep -n 839 -if -o hourlypics_dir/front1/S_exterior11_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extDown_noblind_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior11_direct.smx

dctimestep -n 839 -if -o hourlypics_dir/front1/W_exterior11_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior11_direct.smx

dctimestep -n 839 -if -o hourlypics_dir/front1/N_exterior11_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior11_direct.smx

dctimestep -n 318 -if -o hourlypics_dir/front1/S_exterior12_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extUp_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior12_direct.smx

dctimestep -n 318 -if -o hourlypics_dir/front1/W_exterior12_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_ext_allOpen_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior12_direct.smx

dctimestep -n 318 -if -o hourlypics_dir/front1/N_exterior12_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior12_direct.smx

dctimestep -n 43 -if -o hourlypics_dir/front1/S_exterior13_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extDown_noblind_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior13_direct.smx

dctimestep -n 43 -if -o hourlypics_dir/front1/W_exterior13_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_extDown_noblind_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior13_direct.smx

dctimestep -n 43 -if -o hourlypics_dir/front1/N_exterior13_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
```

```
matrices/daylightmatrix_direct_north.dmx skies/exterior13_direct.smx

dctimestep -n 181 -if -o hourlypics_dir/front1/S_exterior14_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/S_extUp_V80_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/exterior14_direct.smx

dctimestep -n 181 -if -o hourlypics_dir/front1/W_exterior14_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/W_extUp_V80_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/exterior14_direct.smx

dctimestep -n 181 -if -o hourlypics_dir/front1/N_exterior14_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/exterior14_direct.smx

dctimestep -n 1490 -if -o hourlypics_dir/front1/S_existing1_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/existing1_direct.smx

dctimestep -n 1490 -if -o hourlypics_dir/front1/W_existing1_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/existing1_direct.smx

dctimestep -n 1490 -if -o hourlypics_dir/front1/N_existing1_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/existing1_direct.smx

dctimestep -n 2652 -if -o hourlypics_dir/front1/S_existing2_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/V80_all_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/existing2_direct.smx

dctimestep -n 2652 -if -o hourlypics_dir/front1/W_existing2_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/V80_all_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/existing2_direct.smx

dctimestep -n 2652 -if -o hourlypics_dir/front1/N_existing2_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/existing2_direct.smx

dctimestep -n 549 -if -o hourlypics_dir/front1/S_existing3_%04d.hdr
viewpics_dir/viewsurf_south_%03d.hdr bsdf/V80_all_klems.xml
matrices/daylightmatrix_direct_south.dmx skies/existing3_direct.smx

dctimestep -n 549 -if -o hourlypics_dir/front1/W_existing3_%04d.hdr
viewpics_dir/viewsurf_west_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_west.dmx skies/existing3_direct.smx

dctimestep -n 549 -if -o hourlypics_dir/front1/N_existing3_%04d.hdr
viewpics_dir/viewsurf_north_%03d.hdr bsdf/Window_klems.xml
matrices/daylightmatrix_direct_north.dmx skies/existing3.smx
```

9.5.3.2 Combing the three orientations

```
$ cd bashfiles
$ chmod +x render_second.sh
$ ./render_second.sh

#render_second.sh
```

```
#!/bin/bash

for t in {1..767}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior1_${ts}.hdr -o
hourlypics_dir/front1/W_interior1_${ts}.hdr -o
hourlypics_dir/front1/N_interior1_${ts}.hdr >
hourlypics_dir/front1/interior1_${ts}.hdr
done

for t in {1..1691}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior2_${ts}.hdr -o
hourlypics_dir/front1/W_interior2_${ts}.hdr -o
hourlypics_dir/front1/N_interior2_${ts}.hdr >
hourlypics_dir/front1/interior2_${ts}.hdr
done

for t in {1..356}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior3_${ts}.hdr -o
hourlypics_dir/front1/W_interior3_${ts}.hdr -o
hourlypics_dir/front1/N_interior3_${ts}.hdr >
hourlypics_dir/front1/interior3_${ts}.hdr
done

for t in {1..147}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior4_${ts}.hdr -o
hourlypics_dir/front1/W_interior4_${ts}.hdr -o
hourlypics_dir/front1/N_interior4_${ts}.hdr >
hourlypics_dir/front1/interior4_${ts}.hdr
done

for t in {1..298}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior5_${ts}.hdr -o
hourlypics_dir/front1/W_interior5_${ts}.hdr -o
hourlypics_dir/front1/N_interior5_${ts}.hdr >
hourlypics_dir/front1/interior5_${ts}.hdr
done

for t in {1..708}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior11_${ts}.hdr -o
hourlypics_dir/front1/W_interior11_${ts}.hdr -o
hourlypics_dir/front1/N_interior11_${ts}.hdr >
hourlypics_dir/front1/interior11_${ts}.hdr
done

for t in {1..46}
```

```
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior12_${ts}.hdr -o
hourlypics_dir/front1/W_interior12_${ts}.hdr -o
hourlypics_dir/front1/N_interior12_${ts}.hdr >
hourlypics_dir/front1/interior12_${ts}.hdr
done

for t in {1..15}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior13_${ts}.hdr -o
hourlypics_dir/front1/W_interior13_${ts}.hdr -o
hourlypics_dir/front1/N_interior13_${ts}.hdr >
hourlypics_dir/front1/interior13_${ts}.hdr
done

for t in {1..663}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_interior14_${ts}.hdr -o
hourlypics_dir/front1/W_interior14_${ts}.hdr -o
hourlypics_dir/front1/N_interior14_${ts}.hdr >
hourlypics_dir/front1/interior14_${ts}.hdr
done

for t in {1..977}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior1_${ts}.hdr -o
hourlypics_dir/front1/W_exterior1_${ts}.hdr -o
hourlypics_dir/front1/N_exterior1_${ts}.hdr >
hourlypics_dir/front1/exterior1_${ts}.hdr
done

for t in {1..1212}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior2_${ts}.hdr -o
hourlypics_dir/front1/W_exterior2_${ts}.hdr -o
hourlypics_dir/front1/N_exterior2_${ts}.hdr >
hourlypics_dir/front1/exterior2_${ts}.hdr
done

for t in {1..483}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior3_${ts}.hdr -o
hourlypics_dir/front1/W_exterior3_${ts}.hdr -o
hourlypics_dir/front1/N_exterior3_${ts}.hdr >
hourlypics_dir/front1/exterior3_${ts}.hdr
done

for t in {1..593}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior4_${ts}.hdr -o
```

```
hourlypics_dir/front1/W_exterior4_${ts}.hdr -o
hourlypics_dir/front1/N_exterior4_${ts}.hdr >
hourlypics_dir/front1/exterior4_${ts}.hdr
done

for t in {1..40}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior5_${ts}.hdr -o
hourlypics_dir/front1/W_exterior5_${ts}.hdr -o
hourlypics_dir/front1/N_exterior5_${ts}.hdr >
hourlypics_dir/front1/exterior5_${ts}.hdr
done

for t in {1..5}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior9_${ts}.hdr -o
hourlypics_dir/front1/W_exterior9_${ts}.hdr -o
hourlypics_dir/front1/N_exterior9_${ts}.hdr >
hourlypics_dir/front1/exterior9_${ts}.hdr
done

for t in {1..839}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior11_${ts}.hdr -o
hourlypics_dir/front1/W_exterior11_${ts}.hdr -o
hourlypics_dir/front1/N_exterior11_${ts}.hdr >
hourlypics_dir/front1/exterior11_${ts}.hdr
done

for t in {1..318}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior12_${ts}.hdr -o
hourlypics_dir/front1/W_exterior12_${ts}.hdr -o
hourlypics_dir/front1/N_exterior12_${ts}.hdr >
hourlypics_dir/front1/exterior12_${ts}.hdr
done

for t in {1..43}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior13_${ts}.hdr -o
hourlypics_dir/front1/W_exterior13_${ts}.hdr -o
hourlypics_dir/front1/N_exterior13_${ts}.hdr >
hourlypics_dir/front1/exterior13_${ts}.hdr
done

for t in {1..181}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_exterior14_${ts}.hdr -o
hourlypics_dir/front1/W_exterior14_${ts}.hdr -o
hourlypics_dir/front1/N_exterior14_${ts}.hdr >
hourlypics_dir/front1/exterior14_${ts}.hdr
```

```
done

for t in {1..1490}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_existing1_${ts}.hdr -o
hourlypics_dir/front1/W_existing1_${ts}.hdr -o
hourlypics_dir/front1/N_existing1_${ts}.hdr >
hourlypics_dir/front1/existing1_${ts}.hdr
done

for t in {1..2652}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_existing2_${ts}.hdr -o
hourlypics_dir/front1/W_existing2_${ts}.hdr -o
hourlypics_dir/front1/N_existing2_${ts}.hdr >
hourlypics_dir/front1/existing2_${ts}.hdr
done

for t in {1..549}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front1/S_existing3_${ts}.hdr -o
hourlypics_dir/front1/W_existing3_${ts}.hdr -o
hourlypics_dir/front1/N_existing3_${ts}.hdr >
hourlypics_dir/front1/existing3_${ts}.hdr
done

for t in {1..767}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior1_${ts}.hdr -o
hourlypics_dir/front2/W_interior1_${ts}.hdr -o
hourlypics_dir/front2/N_interior1_${ts}.hdr >
hourlypics_dir/front2/interior1_${ts}.hdr
done

for t in {1..1691}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior2_${ts}.hdr -o
hourlypics_dir/front2/W_interior2_${ts}.hdr -o
hourlypics_dir/front2/N_interior2_${ts}.hdr >
hourlypics_dir/front2/interior2_${ts}.hdr
done

for t in {1..356}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior3_${ts}.hdr -o
hourlypics_dir/front2/W_interior3_${ts}.hdr -o
hourlypics_dir/front2/N_interior3_${ts}.hdr >
hourlypics_dir/front2/interior3_${ts}.hdr
done

for t in {1..147}
```

```
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior4_${ts}.hdr -o
hourlypics_dir/front2/W_interior4_${ts}.hdr -o
hourlypics_dir/front2/N_interior4_${ts}.hdr >
hourlypics_dir/front2/interior4_${ts}.hdr
done

for t in {1..298}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior5_${ts}.hdr -o
hourlypics_dir/front2/W_interior5_${ts}.hdr -o
hourlypics_dir/front2/N_interior5_${ts}.hdr >
hourlypics_dir/front2/interior5_${ts}.hdr
done

for t in {1..708}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior11_${ts}.hdr -o
hourlypics_dir/front2/W_interior11_${ts}.hdr -o
hourlypics_dir/front2/N_interior11_${ts}.hdr >
hourlypics_dir/front2/interior11_${ts}.hdr
done

for t in {1..46}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior12_${ts}.hdr -o
hourlypics_dir/front2/W_interior12_${ts}.hdr -o
hourlypics_dir/front2/N_interior12_${ts}.hdr >
hourlypics_dir/front2/interior12_${ts}.hdr
done

for t in {1..15}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior13_${ts}.hdr -o
hourlypics_dir/front2/W_interior13_${ts}.hdr -o
hourlypics_dir/front2/N_interior13_${ts}.hdr >
hourlypics_dir/front2/interior13_${ts}.hdr
done

for t in {1..663}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_interior14_${ts}.hdr -o
hourlypics_dir/front2/W_interior14_${ts}.hdr -o
hourlypics_dir/front2/N_interior14_${ts}.hdr >
hourlypics_dir/front2/interior14_${ts}.hdr
done

for t in {1..977}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior1_${ts}.hdr -o
```

```
hourlypics_dir/front2/W_exterior1_${ts}.hdr -o
hourlypics_dir/front2/N_exterior1_${ts}.hdr >
hourlypics_dir/front2/exterior1_${ts}.hdr
done

for t in {1..1212}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior2_${ts}.hdr -o
hourlypics_dir/front2/W_exterior2_${ts}.hdr -o
hourlypics_dir/front2/N_exterior2_${ts}.hdr >
hourlypics_dir/front2/exterior2_${ts}.hdr
done

for t in {1..483}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior3_${ts}.hdr -o
hourlypics_dir/front2/W_exterior3_${ts}.hdr -o
hourlypics_dir/front2/N_exterior3_${ts}.hdr >
hourlypics_dir/front2/exterior3_${ts}.hdr
done

for t in {1..593}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior4_${ts}.hdr -o
hourlypics_dir/front2/W_exterior4_${ts}.hdr -o
hourlypics_dir/front2/N_exterior4_${ts}.hdr >
hourlypics_dir/front2/exterior4_${ts}.hdr
done

for t in {1..40}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior5_${ts}.hdr -o
hourlypics_dir/front2/W_exterior5_${ts}.hdr -o
hourlypics_dir/front2/N_exterior5_${ts}.hdr >
hourlypics_dir/front2/exterior5_${ts}.hdr
done

for t in {1..5}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior9_${ts}.hdr -o
hourlypics_dir/front2/W_exterior9_${ts}.hdr -o
hourlypics_dir/front2/N_exterior9_${ts}.hdr >
hourlypics_dir/front2/exterior9_${ts}.hdr
done

for t in {1..839}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior11_${ts}.hdr -o
hourlypics_dir/front2/W_exterior11_${ts}.hdr -o
hourlypics_dir/front2/N_exterior11_${ts}.hdr >
hourlypics_dir/front2/exterior11_${ts}.hdr
```

```
done

for t in {1..318}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior12_${ts}.hdr -o
hourlypics_dir/front2/W_exterior12_${ts}.hdr -o
hourlypics_dir/front2/N_exterior12_${ts}.hdr >
hourlypics_dir/front2/exterior12_${ts}.hdr
done

for t in {1..43}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior13_${ts}.hdr -o
hourlypics_dir/front2/W_exterior13_${ts}.hdr -o
hourlypics_dir/front2/N_exterior13_${ts}.hdr >
hourlypics_dir/front2/exterior13_${ts}.hdr
done

for t in {1..181}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_exterior14_${ts}.hdr -o
hourlypics_dir/front2/W_exterior14_${ts}.hdr -o
hourlypics_dir/front2/N_exterior14_${ts}.hdr >
hourlypics_dir/front2/exterior14_${ts}.hdr
done

for t in {1..1490}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_existing1_${ts}.hdr -o
hourlypics_dir/front2/W_existing1_${ts}.hdr -o
hourlypics_dir/front2/N_existing1_${ts}.hdr >
hourlypics_dir/front2/existing1_${ts}.hdr
done

for t in {1..2652}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_existing2_${ts}.hdr -o
hourlypics_dir/front2/W_existing2_${ts}.hdr -o
hourlypics_dir/front2/N_existing2_${ts}.hdr >
hourlypics_dir/front2/existing2_${ts}.hdr
done

for t in {1..549}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)+li(2)+li(3)' -o
hourlypics_dir/front2/S_existing3_${ts}.hdr -o
hourlypics_dir/front2/W_existing3_${ts}.hdr -o
hourlypics_dir/front2/N_existing3_${ts}.hdr >
hourlypics_dir/front2/existing3_${ts}.hdr
done
```

9.5.3. Render-third term

```
dctimestep -n 977 -if -o hourlypics_ds/front1/exterior1_%04d.hdr
viewpics_ds/exterior1_%04d.hdr skies/exterior1_direct_m6.smx

dctimestep -n 1212 -if -o hourlypics_ds/front1/exterior2_%04d.hdr
viewpics_ds/exterior2_%04d.hdr skies/exterior2_direct_m6.smx

dctimestep -n 483 -if -o hourlypics_ds/front1/exterior3_%04d.hdr
viewpics_ds/exterior3_%04d.hdr skies/exterior3_direct_m6.smx

dctimestep -n 593 -if -o hourlypics_ds/front1/exterior4_%04d.hdr
viewpics_ds/exterior4_%04d.hdr skies/exterior4_direct_m6.smx

dctimestep -n 40 -if -o hourlypics_ds/front1/exterior5_%04d.hdr
viewpics_ds/exterior5_%04d.hdr skies/exterior5_direct_m6.smx

dctimestep -n 839 -if -o hourlypics_ds/front1/exterior11_%04d.hdr
viewpics_ds/exterior11_%04d.hdr skies/exterior11_direct_m6.smx

dctimestep -n 318 -if -o hourlypics_ds/front1/exterior12_%04d.hdr
viewpics_ds/exterior12_%04d.hdr skies/exterior12_direct_m6.smx

dctimestep -n 43 -if -o hourlypics_ds/front1/exterior13_%04d.hdr
viewpics_ds/exterior13_%04d.hdr skies/exterior13_direct_m6.smx

dctimestep -n 181 -if -o hourlypics_ds/front1/exterior14_%04d.hdr
viewpics_ds/exterior14_%04d.hdr skies/exterior14_direct_m6.smx

dctimestep -n 5 -if -o hourlypics_ds/front1/exterior9_%04d.hdr
viewpics_ds/exterior9_%04d.hdr skies/exterior9_direct_m6.smx

dctimestep -n 1691 -if -o hourlypics_ds/front1/interior2_%04d.hdr
viewpics_ds/interior2_%04d.hdr skies/interior2_direct_m6.smx

dctimestep -n 663 -if -o hourlypics_ds/front1/interior14_%04d.hdr
viewpics_ds/interior14_%04d.hdr skies/interior14_direct_m6.smx

dctimestep -n 708 -if -o hourlypics_ds/front1/interior11_%04d.hdr
viewpics_ds/interior11_%04d.hdr skies/interior11_direct_m6.smx

dctimestep -n 46 -if -o hourlypics_ds/front1/interior12_%04d.hdr
viewpics_ds/interior12_%04d.hdr skies/interior12_direct_m6.smx

dctimestep -n 298 -if -o hourlypics_ds/front1/interior5_%04d.hdr
viewpics_ds/interior5_%04d.hdr skies/interior5_direct_m6.smx

dctimestep -n 1490 -if -o hourlypics_ds/front1/existing1_%04d.hdr
viewpics_ds/existing1_%04d.hdr skies/existing1_direct_m6.smx

dctimestep -n 2652 -if -o hourlypics_ds/front1/existing2_%04d.hdr
viewpics_ds/existing2_%04d.hdr skies/existing2_direct_m6.smx

dctimestep -n 767 -if -o hourlypics_ds/front1/interior1_%04d.hdr
viewpics_ds/interior1_%04d.hdr skies/interior1_direct_m6.smx

dctimestep -n 549 -if -o hourlypics_ds/front1/existing3_%04d.hdr
```

```
viewpics_ds/existing3_%04d.hdr skies/existing3_direct_m6.smx

dctimestep -n 356 -if -o hourlypics_ds/front1/interior3_%04d.hdr
viewpics_ds/interior3_%04d.hdr skies/interior3_direct_m6.smx

dctimestep -n 147 -if -o hourlypics_ds/front1/interior4_%04d.hdr
viewpics_ds/interior4_%04d.hdr skies/interior4_direct_m6.smx

dctimestep -n 15 -if -o hourlypics_ds/front1/interior13_%04d.hdr
viewpics_ds/interior13_%04d.hdr skies/interior13_direct_m6.smx
```

9.5.4. Render-final results

```
$ cd bashfiles
$ chmod +x render_final.sh
$ bashfiles/render_final.sh


# bashfiles/render_final.sh
#!/bin/bash

for t in {1..767}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior1_${ts}.hdr -o
hourlypics_dir/front1/interior1_${ts}.hdr -o
hourlypics_ds/front1/interior1_${ts}.hdr -o
materialMap/front1/int_allOpen.hdr >
hourlyresult/front1/interior1_${ts}.hdr
done

for t in {1..1691}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior2_${ts}.hdr -o
hourlypics_dir/front1/interior2_${ts}.hdr -o
hourlypics_ds/front1/interior2_${ts}.hdr -o
materialMap/front1/int_allClosed.hdr >
hourlyresult/front1/interior2_${ts}.hdr
done

for t in {1..356}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior3_${ts}.hdr -o
hourlypics_dir/front1/interior3_${ts}.hdr -o
hourlypics_ds/front1/interior3_${ts}.hdr -o
materialMap/front1/int_S_allClosed_W_allOpen.hdr >
hourlyresult/front1/interior3_${ts}.hdr
done

for t in {1..147}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior4_${ts}.hdr -o
hourlypics_dir/front1/interior4_${ts}.hdr -o
hourlypics_ds/front1/interior4_${ts}.hdr -o
```

```
materialMap/front1/int_S_allClosed_W_louvers.hdr >
hourlyresult/front1/interior4_${ts}.hdr
done

for t in {1..298}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior5_${ts}.hdr -o
hourlypics_dir/front1/interior5_${ts}.hdr -o
hourlypics_ds/front1/interior5_${ts}.hdr -o
materialMap/front1/int_S_allClosed_W_V80half.hdr >
hourlyresult/front1/interior5_${ts}.hdr
done

for t in {1..708}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior11_${ts}.hdr -o
hourlypics_dir/front1/interior11_${ts}.hdr -o
hourlypics_ds/front1/interior11_${ts}.hdr -o
materialMap/front1/int_S_louver_W_allOpen.hdr >
hourlyresult/front1/interior11_${ts}.hdr
done

for t in {1..46}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior12_${ts}.hdr -o
hourlypics_dir/front1/interior12_${ts}.hdr -o
hourlypics_ds/front1/interior12_${ts}.hdr -o
materialMap/front1/int_S_V80half_W_allOpen.hdr >
hourlyresult/front1/interior12_${ts}.hdr
done

for t in {1..15}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior13_${ts}.hdr -o
hourlypics_dir/front1/interior13_${ts}.hdr -o
hourlypics_ds/front1/interior13_${ts}.hdr -o
materialMap/front1/int_louvers.hdr >
hourlyresult/front1/interior13_${ts}.hdr
done

for t in {1..663}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/interior14_${ts}.hdr -o
hourlypics_dir/front1/interior14_${ts}.hdr -o
hourlypics_ds/front1/interior14_${ts}.hdr -o
materialMap/front1/int_V80half.hdr >
hourlyresult/front1/interior14_${ts}.hdr
done

for t in {1..977}
do ts=`printf %04d $t `
```

```
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior1_${ts}.hdr -o
hourlypics_dir/front1/exterior1_${ts}.hdr -o
hourlypics_ds/front1/exterior1_${ts}.hdr -o
materialMap/front1/ext_allOpen.hdr >
hourlyresult/front1/exterior1_${ts}.hdr
done

for t in {1..1212}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior2_${ts}.hdr -o
hourlypics_dir/front1/exterior2_${ts}.hdr -o
hourlypics_ds/front1/exterior2_${ts}.hdr -o
materialMap/front1/ext_allClosed.hdr >
hourlyresult/front1/exterior2_${ts}.hdr
done

for t in {1..483}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior3_${ts}.hdr -o
hourlypics_dir/front1/exterior3_${ts}.hdr -o
hourlypics_ds/front1/exterior3_${ts}.hdr -o
materialMap/front1/ext_S_allClosed_W_allOpen.hdr >
hourlyresult/front1/exterior3_${ts}.hdr
done

for t in {1..593}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior4_${ts}.hdr -o
hourlypics_dir/front1/exterior4_${ts}.hdr -o
hourlypics_ds/front1/exterior4_${ts}.hdr -o
materialMap/front1/ext_S_allClosed_W_louvers.hdr >
hourlyresult/front1/exterior4_${ts}.hdr
done

for t in {1..40}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior5_${ts}.hdr -o
hourlypics_dir/front1/exterior5_${ts}.hdr -o
hourlypics_ds/front1/exterior5_${ts}.hdr -o
materialMap/front1/ext_S_allClosed_W_V80half.hdr >
hourlyresult/front1/exterior5_${ts}.hdr
done

for t in {1..5}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior9_${ts}.hdr -o
hourlypics_dir/front1/exterior9_${ts}.hdr -o
hourlypics_ds/front1/exterior9_${ts}.hdr -o
materialMap/front1/ext_W_allClosed_S_louvers.hdr >
hourlyresult/front1/exterior9_${ts}.hdr
done
```

```
for t in {1..839}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior11_${ts}.hdr -o
hourlypics_dir/front1/exterior11_${ts}.hdr -o
hourlypics_ds/front1/exterior11_${ts}.hdr -o
materialMap/front1/ext_S_louver_W_allOpen.hdr >
hourlyresult/front1/exterior11_${ts}.hdr
done

for t in {1..318}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior12_${ts}.hdr -o
hourlypics_dir/front1/exterior12_${ts}.hdr -o
hourlypics_ds/front1/exterior12_${ts}.hdr -o
materialMap/front1/ext_S_V80half_W_allOpen.hdr >
hourlyresult/front1/exterior12_${ts}.hdr
done

for t in {1..43}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior13_${ts}.hdr -o
hourlypics_dir/front1/exterior13_${ts}.hdr -o
hourlypics_ds/front1/exterior13_${ts}.hdr -o
materialMap/front1/ext_louvers.hdr >
hourlyresult/front1/exterior13_${ts}.hdr
done

for t in {1..181}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/exterior14_${ts}.hdr -o
hourlypics_dir/front1/exterior14_${ts}.hdr -o
hourlypics_ds/front1/exterior14_${ts}.hdr -o
materialMap/front1/ext_V80half.hdr >
hourlyresult/front1/exterior14_${ts}.hdr
done

for t in {1..1490}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/existing1_${ts}.hdr -o
hourlypics_dir/front1/existing1_${ts}.hdr -o
hourlypics_ds/front1/existing1_${ts}.hdr -o
materialMap/front1/Window.hdr > hourlyresult/front1/existing1_${ts}.hdr
done

for t in {1..2652}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/existing2_${ts}.hdr -o
hourlypics_dir/front1/existing2_${ts}.hdr -o
hourlypics_ds/front1/existing2_${ts}.hdr -o
materialMap/front1/V80all.hdr > hourlyresult/front1/existing2_${ts}.hdr
```

```
done

for t in {1..549}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front1/existing3_${ts}.hdr -o
hourlypics_dir/front1/existing3_${ts}.hdr -o
hourlypics_ds/front1/existing3_${ts}.hdr -o
materialMap/front1/S_V80all.hdr >
hourlyresult/front1/existing3_${ts}.hdr
done

for t in {1..767}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior1_${ts}.hdr -o
hourlypics_dir/front2/interior1_${ts}.hdr -o
hourlypics_ds/front2/interior1_${ts}.hdr -o
materialMap/front2/int_allOpen.hdr >
hourlyresult/front2/interior1_${ts}.hdr
done

for t in {1..1691}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior2_${ts}.hdr -o
hourlypics_dir/front2/interior2_${ts}.hdr -o
hourlypics_ds/front2/interior2_${ts}.hdr -o
materialMap/front2/int_allClosed.hdr >
hourlyresult/front2/interior2_${ts}.hdr
done

for t in {1..356}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior3_${ts}.hdr -o
hourlypics_dir/front2/interior3_${ts}.hdr -o
hourlypics_ds/front2/interior3_${ts}.hdr -o
materialMap/front2/int_S_allClosed_W_allOpen.hdr >
hourlyresult/front2/interior3_${ts}.hdr
done

for t in {1..147}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior4_${ts}.hdr -o
hourlypics_dir/front2/interior4_${ts}.hdr -o
hourlypics_ds/front2/interior4_${ts}.hdr -o
materialMap/front2/int_S_allClosed_W_louvers.hdr >
hourlyresult/front2/interior4_${ts}.hdr
done

for t in {1..298}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior5_${ts}.hdr -o
hourlypics_dir/front2/interior5_${ts}.hdr -o
```

```
hourlypics_ds/front2/interior5_${ts}.hdr -o
materialMap/front2/int_S_allClosed_W_V80half.hdr >
hourlyresult/front2/interior5_${ts}.hdr
done

for t in {1..708}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior11_${ts}.hdr -o
hourlypics_dir/front2/interior11_${ts}.hdr -o
hourlypics_ds/front2/interior11_${ts}.hdr -o
materialMap/front2/int_S_louver_W_allOpen.hdr >
hourlyresult/front2/interior11_${ts}.hdr
done

for t in {1..46}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior12_${ts}.hdr -o
hourlypics_dir/front2/interior12_${ts}.hdr -o
hourlypics_ds/front2/interior12_${ts}.hdr -o
materialMap/front2/int_S_V80half_W_allOpen.hdr >
hourlyresult/front2/interior12_${ts}.hdr
done

for t in {1..15}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior13_${ts}.hdr -o
hourlypics_dir/front2/interior13_${ts}.hdr -o
hourlypics_ds/front2/interior13_${ts}.hdr -o
materialMap/front2/int_louvers.hdr >
hourlyresult/front2/interior13_${ts}.hdr
done

for t in {1..663}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/interior14_${ts}.hdr -o
hourlypics_dir/front2/interior14_${ts}.hdr -o
hourlypics_ds/front2/interior14_${ts}.hdr -o
materialMap/front2/int_V80half.hdr >
hourlyresult/front2/interior14_${ts}.hdr
done

for t in {1..977}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior1_${ts}.hdr -o
hourlypics_dir/front2/exterior1_${ts}.hdr -o
hourlypics_ds/front2/exterior1_${ts}.hdr -o
materialMap/front2/ext_allOpen.hdr >
hourlyresult/front2/exterior1_${ts}.hdr
done

for t in {1..1212}
do ts=`printf %04d $t `
```

```
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior2_${ts}.hdr -o
hourlypics_dir/front2/exterior2_${ts}.hdr -o
hourlypics_ds/front2/exterior2_${ts}.hdr -o
materialMap/front2/ext_allClosed.hdr >
hourlyresult/front2/exterior2_${ts}.hdr
done

for t in {1..483}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior3_${ts}.hdr -o
hourlypics_dir/front2/exterior3_${ts}.hdr -o
hourlypics_ds/front2/exterior3_${ts}.hdr -o
materialMap/front2/ext_S_allClosed_W_allOpen.hdr >
hourlyresult/front2/exterior3_${ts}.hdr
done

for t in {1..593}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior4_${ts}.hdr -o
hourlypics_dir/front2/exterior4_${ts}.hdr -o
hourlypics_ds/front2/exterior4_${ts}.hdr -o
materialMap/front2/ext_S_allClosed_W_louvers.hdr >
hourlyresult/front2/exterior4_${ts}.hdr
done

for t in {1..40}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior5_${ts}.hdr -o
hourlypics_dir/front2/exterior5_${ts}.hdr -o
hourlypics_ds/front2/exterior5_${ts}.hdr -o
materialMap/front2/ext_S_allClosed_W_V80half.hdr >
hourlyresult/front2/exterior5_${ts}.hdr
done

for t in {1..5}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior9_${ts}.hdr -o
hourlypics_dir/front2/exterior9_${ts}.hdr -o
hourlypics_ds/front2/exterior9_${ts}.hdr -o
materialMap/front2/ext_W_allClosed_S_louvers.hdr >
hourlyresult/front2/exterior9_${ts}.hdr
done

for t in {1..839}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior11_${ts}.hdr -o
hourlypics_dir/front2/exterior11_${ts}.hdr -o
hourlypics_ds/front2/exterior11_${ts}.hdr -o
materialMap/front2/ext_S_louver_W_allOpen.hdr >
hourlyresult/front2/exterior11_${ts}.hdr
done
```

```
for t in {1..318}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior12_${ts}.hdr -o
hourlypics_dir/front2/exterior12_${ts}.hdr -o
hourlypics_ds/front2/exterior12_${ts}.hdr -o
materialMap/front2/ext_S_V80half_W_allOpen.hdr >
hourlyresult/front2/exterior12_${ts}.hdr
done

for t in {1..43}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior13_${ts}.hdr -o
hourlypics_dir/front2/exterior13_${ts}.hdr -o
hourlypics_ds/front2/exterior13_${ts}.hdr -o
materialMap/front2/ext_louvers.hdr >
hourlyresult/front2/exterior13_${ts}.hdr
done

for t in {1..181}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/exterior14_${ts}.hdr -o
hourlypics_dir/front2/exterior14_${ts}.hdr -o
hourlypics_ds/front2/exterior14_${ts}.hdr -o
materialMap/front2/ext_V80half.hdr >
hourlyresult/front2/exterior14_${ts}.hdr
done

for t in {1..1490}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/existing1_${ts}.hdr -o
hourlypics_dir/front2/existing1_${ts}.hdr -o
hourlypics_ds/front2/existing1_${ts}.hdr -o
materialMap/front2/Window.hdr > hourlyresult/front2/existing1_${ts}.hdr
done

for t in {1..2652}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/existing2_${ts}.hdr -o
hourlypics_dir/front2/existing2_${ts}.hdr -o
hourlypics_ds/front2/existing2_${ts}.hdr -o
materialMap/front2/V80all.hdr > hourlyresult/front2/existing2_${ts}.hdr
done

for t in {1..549}
do ts=`printf %04d $t `
pcomb -e 'lo=li(1)-li(2)+li(3)*li(4))' -o
hourlypics/front2/existing3_${ts}.hdr -o
hourlypics_dir/front2/existing3_${ts}.hdr -o
hourlypics_ds/front2/existing3_${ts}.hdr -o
materialMap/front2/S_V80all.hdr >
hourlyresult/front2/existing3_${ts}.hdr
```

```
done
```

10. Arranging the annual images

```
$ bashfiles/mv_int.sh
$ bashfiles/mv_int2.sh
$ bashfiles/mv_ext.sh
$ bashfiles/mv_ext2.sh
$ bashfiles/mv_ext.sh
$ bashfiles/mv_ext2.sh

Example:
# bashfiles/mv_int.sh
mv hourlyresult/front1/interior1-0001 Rendering/interior/int_1_1_8.hdr
mv hourlyresult/front1/interior1-0002 Rendering/interior/int_1_1_9.hdr
.
.
.

# bashfiles/mv_int2.sh
mv int_1-1-8.hdr int_1.hdr
mv int_1-1-9.hdr int_2.hdr
mv int_1-1-10.hdr int_3.hdr
.
.
.
```

11. Calculating the Glare metric

```
# bashfiles/glare.sh
#!/bin/bash

for t in {1..4691}
do
evalglare -b 2000 -G 2 -vf views/front1.vf
Rendering/interior/int_$t.hdr > Rendering/glare/interior/int_$t.txt
done

for t in {1..4691}
do
evalglare -b 2000 -G 2 -vf views/front1.vf
Rendering/exterior/ext_$t.hdr > Rendering/glare/exterior/ext_$t.txt
done

for t in {1..4691}
do
evalglare -b 2000 -G 2 -vf views/front1.vf
Rendering/existing/exist_$t.hdr > Rendering/glare/existing/exist_$t.txt
done
```

CURRICULUM VITAE

Leyla Sanati

Place of birth: Tehran, Iran

Education:

M.S., University of Shahid Behesti, Iran, August 2006. Major: Architecture

Dissertation Title: Subdivided Windows with Mixed Shading Devices: A Daylighting Solution for Effective Integration of Occupants into the Building Environmental Control

Experience:

Instructor **Jan. 2014 – May 2014**
University of Wisconsin-Milwaukee, Department of Architecture
- ARCH 390/790: Modeling Architectural Illumination with Radiance

Co-Instructor **Jan. 2013 – May 2013**
University of Wisconsin-Milwaukee, Department of Architecture
- ARCH-522: Environmental Systems: Lighting and Acoustical Design

Instructor **Jan. 2012 – May 2012**
University of Wisconsin-Milwaukee, Department of Architecture
- ARCH-722: Daylighting and Architectural Design

Intern **May 2011 – August 2011**
Sustainable Engineering Group LLC, Madison, WI
- Energy modeling

Project Assistant **Sep. 2010 – May 2011**
University of Wisconsin-Milwaukee, Department of Architecture
- Carbon Neutral Design - Building Case Study

Instructor **Jan. 2010 – May 2010**
University of Wisconsin-Milwaukee, Department of Architecture
- ARCH-520: Environmental Control Systems: Illumination and Thermal Comfort

Teaching Assistant **Jan. 2008 – Dec. 2009**
University of Wisconsin-Milwaukee, Department of Architecture
- ARCH-522: Environmental Systems: Lighting and Acoustical Design (Fall 2009)
- ARCH-520: Environmental Systems: Illumination and Thermal Comfort (Spring 2009)

- ARCH-520: Environmental Systems: Illumination and Thermal Comfort (Fall 2008)
- ARCH-210: Introduction to Building Technologies (Spring 2008)

Graduate Design Consultant **Summer 2008, Summer 2009, and Fall 2011**
CDS (Community Design Solutions), School of Architecture and Urban Planning, UW-Milwaukee

Architect **Dec. 2003 – Jun. 2005**
Iran Amayesh Consulting Engineers, Tehran, Iran

Memberships:

Illuminating Engineering Society of North America (IES)
Society of Building Science Educators (SBSE)

Publications:

Sanati, L., & Utzinger, D. M. (2013). The Effect of Window Shading Design on Occupant Use of Blinds and Electric Lighting. *Building and Environment*. Vol. 64, June 2013, pp. 67-76.

Sanati, L., & Utzinger, D. M. (2009). The Impact of Occupants' Behavior on Electric Light Usage: A case study of three Milwaukee, Wisconsin Nature Centers. Proceedings of PLEA2009: *26th Conference on Passive and Low Energy Architecture, Quebec City, Canada*

Tahbaz, M., & Sanati, L. (2007). Room and Window Design According to Sunshine, Shadow, and Daylight. *Light & Engineering*. Vol. 16, No. 1, pp. 96-105.