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THE IMPACT OF TRANSLUCENT FABRIC SHADES AND CONTROL STRATEGIES ON ENERGY SAVINGS AND VISUAL QUALITY

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ABSTRACT

Translucent fabric shades provide opportunities for building occupants to control sunlight penetration for heat reduction, thermal comfort, and visual quality. Regulating shades affects building energy and can potentially reduce the size of mechanical cooling systems. Shades are not normally included in energy model studies during the design process, even though shades potential impact energy use. This is because the occupants normally leave shades closed a large fraction of the time, but models are generally performed with no shades. Automatic shade control is now available, so it is necessary to understand the impact of shades on visual quality and their energy saving potential in order to optimize their overall performance. There are very limited studies that have address shades and their integrated performance on energy consumption and visual quality. Most of these do not reflected modern shade types and their application.

The goals of this study are: First, to determine the impact of shades on total, heating, cooling and lighting energy savings with different design and operation parameters. Second, to study and develop different automatic shade control strategies to promote and optimize energy savings and visual quality.

A simulation-based approach using EnergyPlus in a parametric study provide better understanding energy savings under different shade conditions. The parametric runs addressed various building parameters such as geometry, orientation, site climate, glazing/shade properties, and shade control strategies with integrated lighting control. The impact of shades was determined for total building and space heating, cooling and lighting energy savings. The effect of shades on visual quality was studied using EnergyPlus, AGI32 and DAYSIM for several indices such as daylight glare index (DGI), work plane illuminance, luminance ratios and view. Different shade control strategies and integrated lighting control were considered with two translucent fabric shade colors.

The results clearly show the benefit of automatic shade control strategies with integrated lighting control over a condition when shades are closed all day. The main contributor to the total energy savings is from lighting energy savings, followed by cooling energy savings. Shades provide greater benefit in a hot climate and in a moderate climate than in a cold climate. Different control strategies provide savings in the range of 7-35% for annual total space energy with higher savings with light colored shades. Control strategies of shades should be selected and optimized based on climate, orientation, window area, and window/shade properties. High performance glazings, when equipped with shades, show lower energy savings when compared to standard glazings. High transmittance/reflectance shades, such as white shades, perform better than dark shades in most of the cases due to higher lighting energy savings obtained with the automatic electric lighting control and the resulting cooling energy savings from rejection of some solar energy and a reduction in the heat from lights. A South orientation showed the least benefit of automatic control of shades when compare to other orientations due to the large fraction of time shades are required to provide visual comfort. Under automatic shade control, energy savings are higher the more often the shades can be raised. The different automatic control strategies present tradeoffs between energy savings and comfort.

With regard to visual quality, daylight quality assessments on view, glare, luminance ratios, and UDI can be used to assess shade control strategies. Automatic shade control can increase the number of view hours while controlling sunlight penetration. With automatic shade control, more daylight hours can be provided within the beneficial range of 100-2000 lux compared to shades that are closed all day. For a person facing the window, discomfort glare is likely to increase the more often the shades are raised. Keeping the shades down ensures an acceptable glare condition, but limits energy savings. Luminance ratios are another metric that can be used to assess shade performance. With white shades, the luminance ratios between the task and proximate surfaces are improved. Dark shades help improve the luminance ratios between the task and distant surfaces. When the shades are left open, even with no direct sunlight in the space, task to window luminance ratios will often exceed 1:10.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

INTRODUCTION

Windows greatly affect energy use in buildings, especially for heating, cooling and lighting energy use. According to the U.S. Department of Energy, 32% of the cooling load and 22% of the heating load come from the impact of windows (DOE 2007). Proper design and selection of windows can help reduce solar heat gain and thermal losses (Carmody 2004). Research has shown that daylight, through the use of lighting control, can significantly reduce lighting energy, which accounts for 16% of annual electrical energy consumption in the building sector within the US (DOE 2006). Daylight may also enhance an occupant's well being and productivity (Heschong Mahone Group 2003). However, excessive daylight, or the use of inefficient glazing material, could result in high solar heat gain, no energy savings, and poor visual quality.

In work spaces, windows typically require some type of interior or exterior shading device to provide privacy, to enhance aesthetics, or to give varying degrees of sunshine and daylight control (Ozisik and Schutrum 1960).

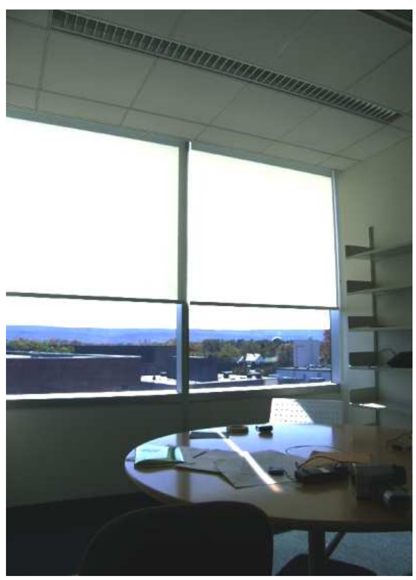

Fig 1-1: Translucent shade application helps give varying degrees of sunshine control.

Translucent fabric shades [Figure **1-1**] have become quite popular due to their availability, ease of operation, low cost, ease of maintenance and their aesthetic appearance (Mills and McCluney 1993). Translucent fabric shades will be referred to throughout this dissertation as "translucent shades" or "shades" for short. As an interior shading device, shades offer the opportunity for occupants to increase visual quality and improve thermal comfort. They enable occupants to shield direct sunlight, control glare and reduce solar heat gain. Unfortunately, occupants generally adjust their shades infrequently (Rubin, Collins et al. 1978; Rea 1984) resulting in poor daylight admission. This not only causes higher lighting energy use, but also restricts or eliminates the exterior view. In order to maximize energy savings, automatic shade control and photosensor-based lighting controls are needed. In addition to lighting savings, cooling energy savings may occur due to reductions in solar and lighting loads compared to static control of shading and lighting systems (Lee and Selkowitz 1995). If the performance of translucent shades together with lighting control systems is better understood, then more energy savings can be achieved in commercial building applications.

1.1 Background

Energy performance of translucent shades together with windows has been studied to some extent, and showed energy savings potential in the past (Ozisik and Schutrum 1959; Ozisik and Schutrum 1960; Farber, Smith et al. 1963; Pennington, Smith et al. 1964; Yellott 1965; Moore and Pennington 1967). Translucent shade fabrics and window glazings nowadays are very different than in those studies. Modern shade fabrics, when incorporated with different type of window glazings, yield optically complex systems. The fabric comes in a variety of colors with holes that preserve the view image and control direct beam solar gain [Figure **1-2**]. The characteristics that define shade properties include optical and thermal properties of the window and shade systems. The optical properties are transmittance, reflectances, absorptance and openness factor. The thermal properties are solar heat gain coefficient and thermal transmission (U-factor). The interaction of a window and shade unit with other building parameters such as building location, geometry, zoning, and control strategies is crucial. These different factors affect heat gain, visual quality and glare.

Automated control of shades and lighting provides solutions for the infrequent adjustment of shades which result in the poor control of daylight and solar gain that affects energy use. Research on automatic control of shading devices, glazing and lighting control systems have shown significant cooling and lighting energy savings, when compared with no shade or lighting control system (Lee and Selkowitz 1995; Lee and Selkowitz 2006).

Typically, the impact of translucent shades on a building's energy consumption is not commonly considered during the design of a building, or in a green building rating system such as LEED (Haselbach 2008). One reason is that shades can be easily operated by the occupants. A study on the impact of translucent shades can provide a better understanding of how much energy can be saved and how shades can be automatically controlled to optimize energy savings.

The impact on visual quality has been studied to some extent, however, only a few studies addressed translucent fabric shades (Carmody 2004; Tavil and Lee 2006; Lee and Tavil 2007).

This thesis examines translucent fabric shade performance which includes the impact on a building's energy consumption and visual quality. A simulation-based approach is used with parametric studies to provide a better understanding of how to automatically control and optimize translucent shades for energy conservation in commercial building applications, and what impact their control strategies have on visual quality.

Fig 1-2: Examples of translucent shade fabric.

1.2 Objectives

The objective of this dissertation is to understand the impact of translucent shades and their control strategies on building energy performance as well as visual quality. The goal is to optimize the savings in heating, cooling, lighting and total energy by using automated shade control strategies together with integrated lighting control systems, and to provide acceptable visual quality for commercial building applications. The detailed objectives are as follows:

1. Determine annual heating, cooling, lighting and total energy loads and savings for translucent shades, based on different climate, building and space parameters for a window and shade unit on a commercial building using an energy simulation program.

2. Study and develop different control strategies with the aim to promote energy savings and visual quality.

3. Quantify and optimize energy savings received from different automatic shade control strategies with integrated lighting control systems while providing acceptable visual quality.

1.3 Contributions

This dissertation has three main contributions:

1. It explores the impact of translucent shades on building energy use across a variety of different climates and parameters.
2. It quantifies the performance achieved by different automated shade strategies in conjunction with electric lighting control for both energy savings and visual quality.
3. Through the use of a simulation-based approach, it presents shade and lighting control strategies which provide good energy performance and visual quality across a variety of parameters.

1.4 Research hypotheses

The main research hypothesis is that translucent shades and automated lighting control can improve energy performance of windows.

The subsidiary hypothesis is that the energy performance and preferred control strategy for translucent shades will vary with parameters such as climate, geometry, orientation, window and translucent shade types, and other important parameters. Additionally, automated shade control strategies can guarantee energy savings and visual quality.

Finally, energy savings can be optimized to specific climates with selective control of the shades based on measurable quantities and still provide acceptable visual quality.

1.5 Scope and limitations

The scope of this dissertation is focused on the impact of translucent shades and their control strategies with integrated lighting control systems for commercial office spaces. The study addresses different climate, geometry, orientation, window/shade types and control strategies to optimize energy savings and visual quality. The study includes a literature review, research methodology, the critical parameters to be addressed in building energy simulations programs, impact of the use of translucent shades on building energy and the development of a control strategy for simultaneously optimizing energy and visual quality. The theoretical control strategies mentioned in this dissertation may or may not reflect the commercial applications available on the market at this point.

For the energy savings provided by different parameters and shade control strategies, the effect on annual heating, cooling, lighting and total building electric energy are studied using Energy Plus, an energy simulation program.

For the visual comfort portion of this study, the effect of translucent shades and their control on work plane illuminance, daylight glare index (DGI), luminance ratios and view to the outside are studied using the AGI32, DAYSIM and Energy Plus simulation programs.

Due to time, cost and weather data availability, this study applies simulated weather data for five cities that represent most of the climatic and daylight utilization conditions in the United States. The results might not accurately reflect electric energy savings within other regions because of climate and daylight availability differences. The methodology and knowledge gained, however, can be applied to other regions internationally.

1.6 Approach

The dissertation consists of two parts. The first part studied the impact of translucent shades and their control strategies across different parameters such as climate, geometry, orientation, window/shade types and control strategies on annual electric energy savings using the EnergyPlus building energy simulation program. This part approached the problem by analyzing at the annual total energy savings that occurs from the use of translucent shades and different shading control strategies, when an automated electric lighting control system is also applied.

The second part consists of a detailed analysis of the impact of translucent shades and their control strategies with the aim to optimize the energy savings and provide better visual quality.

Finally, a discussion on the impact of translucent shade control strategies for the optimization of both energy and visual comfort, and additional considerations for future automated shade control systems, are discussed.

1.7 Organization of this dissertation

This dissertation is composed of six chapters and two appendix sections.

Chapter one introduces background information, objectives, contributions, hypotheses, scope and limitations and approach of the research.

Chapter two reviews translucent shade characteristics and properties and previous work of researchers on energy performance of translucent shades, existing work on automated shading control systems, simulation studies of translucent shades, studies on visual quality and the gaps in this literature.

Chapter three provides a detailed explanation of the simulation parameters, the methodology applied in the simulation studies, shade control strategies and simulation tools.

Chapter four presents the simulation results of the different shade control strategies targeting energy savings.

Chapter five provides the development, detailed results and visual quality impact analysis of shade control strategies for energy savings and visual quality.

Chapter six contains conclusions, discussion and recommendations for future work.

Lastly, appendix sections A and B provide additional tabular data on the simulation cases of chapters four and five.

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Chapter 2

LITERATURE REVIEW

This chapter discusses the previous literature on many aspects of translucent fabric shades, their properties, control strategies, energy performance and other related issues. The chapter consists of four parts: the first part provides an overview of translucent shades, their physical properties, and how to determine these properties for energy simulations. The second part reviews shade and lighting control strategies and their impact on building energy performance. The third part reviews simulation studies of shades, and the final part summarizes the literature on visual quality and the indices used to measure visual quality with translucent shades.

2.1 Translucent shades

Translucent fabric shades sometimes are known as "roller shades", and are called "translucent shades" or "shades" for short throughout this thesis. They can be categorized as an interior shading device and are widely used in commercial and residential building applications for controlling solar heat gain and glare from windows and also for providing privacy.

Translucent shades are typically woven sheets of fabric that wrap around tubes that may contain a spring or motorized core and can be set at any desired height either manually or automatically [Figure **2-1**]. The fabric is typically made of vinyl-coated polyester yarns with a variety of weave patterns, colors, openness factor, number of layers and installation methods that vary by manufacturer. The selection options depend on the degree of privacy, attenuation of sunlight, solar heat gain control, daylight, view to exterior and aesthetic purpose. This study focused on interior fabric translucent shades only.

2.1.1 The physical properties of translucent shades

There are certain key properties of translucent shades that must be addressed in the design and selection of simulations. This part of the literature review addresses these properties.

2.1.1.1 Thermal properties

When shades are presented in a space, the solar radiation that passes through a glazing unit strikes the shades and increases its surface temperature. Since shades can be defined together with windows as a single system, certain thermal properties of windows are also applied to a window-shade combination. These thermal properties are:

Fig 2-1: An interior translucent fabric shade and automated shade control application (Photo credit (right): Lutron™).

- **Thermal transmission (U-factor)**

U-factor represents the rate of thermal heat transfer through windows and shades. When there are temperature differences between the inside and the outside, heat is lost or gained through windows, frames and shades. The heat transfer occurs due to the combined effects of conduction, convection and radiation. Most windows have three U-factors associated with them, the center-of-glass, the edge-of-glass and the frame U-factors. The units of U-factor are $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot °F$). The lower the U-factor, the more energy-efficient the glazing is. Thermal resistance (R-value) is the inverse of U-factor and is a measurement of heat flow resistance.

- **Solar heat gain coefficient (SHGC)**

SHGC is the fraction of incident solar radiation entering a building through the whole window assembly. The term is expressed in a dimensionless number from 0 to 1. Higher numbers mean higher heat gain. The SHGC is influenced by the same factors as the shading coefficient (SC), but SC is a relative measure to a standard single pane of glass. SHGC is equal to SC multiplied by 0.87.

2.1.1.2 Optical properties

The optical properties associated with windows and shades that affect radiant energy transfer are:

- **Transmittance (τ)**

Transmittance can be defined with regard to both light and total energy. For windows, the visible transmittance (Tvis), the UV transmittance and total solar energy transmittance may all be available. To describe shades, this study uses the visible transmittance (Tvis) in particular, which refers to the percentage of optical radiation that passes through the shade material. Holes provide the possibility for a reduced direct radiation beam.

- **Reflectance (ρ)**

Reflectance is the percentage of light or energy reflected off the surface. Many types of reflection can occur, although in this study, transmittance is assumed to be Lambertian.

- **Absorptance (α)**

Absorptance is the percentage of energy that is neither transmitted nor reflected and is therefore absorbed and transformed to heat that may then be radiated into the space.

2.1.2 Determination of translucent shade physical properties

Researchers attempted to define these shade physical properties through experiments and measurements. The research in this area and the relevant parameters are presented in this section.

The determination of thermal-optical properties of the window-shade combination has been done since the 1950's.

For translucent shades, the effect of different materials and colors and their impact on heat gain and loss when combined with different types of glass and various glass-shade openings were first studied by Ozisik and Schutrum (Ozisik and Schutrum 1959). Shade fabrics used in this study were opaque. High U-factor glazing units were also used. The study found that the U-factor of a fully drawn aluminum foil shade (highly reflective) was lower and more effective for reducing heat loss through a window. The U-value of a half-drawn shade was the average of the fully drawn shade and a window with no shade. The study also found that varying the shade and the glass spacing from 19 cm (0.75") to 7.6 cm (3") did not change the heat gain for solar radiation, while higher heat gain (by 5-10%) occurred with a 14.6 cm (5 ¾ in) spacing with the shade hung without a sealed edge. With no solar radiation, there is no effect on heat gain with spacing of 1.9, 7.6 and 14.6 cm (0.75", 3" and 5 ¾").

Double-pane glazings with shades were studied by Farber (Farber, Smith et al. 1963). The study presented the mathematical analysis of total heat gain of double-pane glazing with interior shading devices such as Venetian blinds, folded and flat draperies and compared these results with measurements. A solar calorimeter was also used in this study.

Moore and Pennington (Moore and Pennington 1967) focused on standard methods to measure solar transmittance and reflectance of a single-pane and a double-pane glass and shade combination. The study included a detailed investigation of solar optical properties by means of different instruments. The study considered the effect of the solar incident angle and shading configuration as suspended in a space. An artificial light source was used in this comparison. Shades in this study were classified as open, semi-open and closed weave, and by color as dark, medium and light. However, these terms do not fully reflect the true solar optical properties of the fabrics which determine solar heat gain through them. The paper proposed to classify fabrics as a function of transmittance, reflectance, absorptance and openness. The openness of the fabric provided a close correlation to the fabric's transmittance, and could be used to indicate the solar heat transmittance. Incident angles and folding drapes affected the solar optical properties. Reflectance of the shade material was the dominant characteristic affecting the solar heat gain, while transmittance was less important. When transmittance decreased, the absorptance increased and contributed to solar heat gain. Unfortunately, these studies do not reflect modern shade characterizations and applications.

For more modern shade and window characterization, Klems (Klems and Keller 1987; Klems and Kelley 1996) studied the thermal performance of single and double glazing using a calorimetric apparatus called "the Mobile Window Thermal Test" (MoWiTT) Facility. The MoWiTT was built at Lawrence Berkeley Laboratory and later moved to Nevada for further experiments. A problem mentioned for MoWiTT was that the technique could not accurately measure high performance systems such as a highly insulated, low SHGC glazing unit since it was hard to isolate the fenestration performance from the impact of the shading device because of small load differences, especially at night. The study presented the derived equations which can be extended to determine the solar heat gain coefficients from non-calorimetric measurements of solar-optical properties of complex fenestration components (i.e. with translucent roller shades and blinds). The procedure was termed solar-thermal separation.

Currently, ASHRAE (ASHRAE 2005) provides approximate multipliers for shading calculations which are called Interior Solar Attenuation Coefficients (IAC) and are based on Klems's limited measurement data on complex fenestration system (Klems 1995; Klems, Warner et al. 1996; Klems and Warner 1997; Klems 2002).

IAC is a ratio of SHGC for the glazing with shades to the SHGC of the glazing alone. IAC was expected to be independent of incident angle because the IAC subsystems were based on a uniform diffusing outer layer. The IAC table in the ASHRAE Handbook is helpful for a designer but not comprehensive. It does not cover all of the possible window and shade combinations.

Allarie (Allarie 1992) provided detailed procedures of solar heat gain coefficient measurement using a solar calorimeter and simulated solar irradiance. The procedures can be applied to window and shade combinations.

Harrison (Harrison 1995) studied the SHGC for a window with Venetian blinds and flat translucent shades. The optical properties of the fabrics are unknown. The shade was positioned with a sealed edge and non sealed edge at 8.5 cm (3.5") and 18.5 cm (7.5") distance from the glass. The SHGC of these shade positions was 0.23 and 0.29 respectively. The size of the gap was somewhat unrealistic, given the position of the shade.

Harrison and Van Wonderen (Harrison and Van Wonderen 1996) studied the solar heat gain of complex fenestrations with shadings. The purpose was to establish a listing of performance test results for generic shading products and compare the measured results with calculated values using analytical methods. This study included the investigation of complex glazings with shading devices. The methodology was to measure the SHGC using the calorimeter test cell with an artificial light source. This study established the feasibility of using a solar simulator for SHGC measurements. The experiments were conducted indoors using the stationary, guarded and steady-state design options of a calorimeter. Tests were done using both normal incident radiation and an angle dependent test method. Test samples were selected from commercially available glazing and shading systems (i.e., heat absorbing insulated glazing-units (IGU's), reflective film and suspended film IGU's and shading devices (i.e., blinds and shades)). Shade fabrics used in this study were a white translucent cloth, a white opaque vinyl shade, a dark brown opaque vinyl shade and a silver cloth shade. The opaque one provided zero transmittance and the rest of the samples varied in transmittance from 0.16 to 0.24 and in reflectance from 0.12 to 0.70. Shades were mounted with a 1.27 cm (0.5") distance to the glass. The edge was sealed within the window frame of the calorimeter.

A solar simulator was used for replacing the sunlight in an indoor measurement. Hakansson (Håkansson 1999) used the solar simulator for calorimetric measurements on window and shading devices. This paper described the use of a solar simulator to determine the SHGC of fenestrations. Two types of lamp were compared in the study, the Philips MSR metal halide lamp and the three combinations of a sulfur plasma lamp, an incandescent dichroic mirror lamp and an incandescent lamp with an aluminum reflector. To match the solar spectrum, the author proposed the use of three combination lamps because of its advantage on life, spectrum and repeatable light level. Although the sulfur lamp model has been discontinued, the author expected to be able to obtain the improved version from the manufacturer.

Tait (Tait 2006) conducted measurements of SHGC and U-factor of glazings and window attachment products including translucent fabric shades. The methodology was to use two exterior solar calorimeters with a hot guarded method to determine the SHGC of attachment products. Two types of roller shades were used, a solid shade and an open weave shade together with the different types of glazing from the standard single-pane to double-pane with a low emittance coating (Low-E). The difference in the openness factor or the type of weave in this study affected the SHGC and the U-factor. The lower SHGC and U-factor occurred with most glazings and solid shades. The exception occurred with the double-pane bronze and clear glazings where the open weave shades showed slightly lower SHGC. The reduction of SHGC and U-factor when shades are applied compared to the glass alone ranged from 9% to 44% and 4% to 27% for the better performance and the poorer performance glazings. The study, however did not mention either the optical properties or the openness of both shades and the benefit of using the open weave type on daylighting and visual quality was not considered.

In summarizing the previous research, these studies covered relevant shade and window combinations but did not address them completely. The studies showed that suitable distance and edge-seal can be determined to optimize the energy savings but with a small impact on energy savings. They also show that a shade's optical and thermal properties have a significant impact on energy savings. The impact of a window and shade combination can be determined by the use of a solar calorimeter with real or simulated solar and room-size instruments which are hard to build, measure, and are very time consuming and may not be suitable for many emerging window and shade combinations.

With advancements in thermal modeling and energy simulation, a simulation-based approach should provide a good solution for a parametric study of a shade's impact of shade and window combination.

2.2 Translucent shade and lighting control strategies and energy performance

Studies on automated control of shading devices and electric lighting systems have been conducted by several researchers and include advanced devices such as electrochromic windows (Sullivan, Lee et al. 1994; Lee and Selkowitz 1995; Lee, Dibartolomeo et al. 2006). These studies are mostly done with window blinds and electrochromic windows, which to some extent can be compared to that of translucent shades as they impact interior illuminance and solar transmission in a similar manner. These studies showed that performance of different control strategies impact cooling and lighting energy, with the lighting energy savings dominating.

For exterior roller shades, Tzempelikos (Tzempelikos and Athienitis 2007) controlled window transmittances to represent two shade control strategies, passive (always closed) and automatic (open when the direct beam radiation incident on the window is less than 20 W/m^2) with an active on/off lighting control system. The authors reported the energy benefits of daylighting with automatic shading and lighting control outweighing any increased energy use due to solar gain. The results also showed that on a south-facing office in Montreal with 30% glass area and 20% shade transmittance, automatic shade and lighting control accounted for 60% lighting energy savings when compared to no shading and passive lighting control.

Lee conducted research (Lee and Selkowitz 1995) on electrochromic glazing and automated venetian blinds coupled with daylighting controls using DOE-2 simulations. The best control strategy suggested was a simple control that admitted sufficient daylight and decreased solar gain. Performance, however, was highly dependent on the optical and thermal characteristics of the window system. The later work of Lee et al (Lee, DiBartolomeo et al. 1998) and DiBartolomeo et al. (DiBartolomeo, Lee et al. 1998) further compared the energy and lighting performance of static and automated venetian blind systems under different sky conditions. Static control kept the blinds at a specific angle at all times. The automatic shading systems were controlled based on the dynamic balance between solar heat gain and daylight level. The results showed that automatic control of blinds and the electric lighting system significantly reduced the energy required for cooling up to 32%, with lighting energy savings up to 52%, and peak electrical demand reduced by as much as 32%.

Sullivan et al. (Sullivan, Lee et al. 1994) studied different control strategies for electrochromic glazings. The analysis included the energy savings from cooling, lighting, total electricity use and peak demand for electrochromic glazings as a function of glazing type, size and control strategy. The author used DOE-2.1E to simulate energy use of perimeter offices in a heating-dominated climate. The control strategy was based on the daylight illuminance, the incident total solar radiation, and the space cooling load. The study found that the setpoint range for the total solar radiation control must correlate with the window size. For a building with a low window-to-wall ratio (WWR), a high setpoint for total solar radiation was the best option since it provided an adequate amount of daylight without higher heat gain and a lower setpoint can be applied for a high WWR.

Galasiu et al. evaluated the lighting energy savings of interior window blinds with various static blind configurations and daylight control systems. The results showed that electric lighting energy savings can vary from 5% to 45% depending on blind position and the type of lighting control. The savings in lighting energy were more significant when used with photo-control than automatic on/off and always-on control. (Galasiu, Atif et al. 2004).

Lee's study on the New York Times building showed a properly applied automatic window shading system with an automatic lighting control can result in lighting energy savings of 30-60% (Lee and Selkowitz 2006). This research also leaded to the SolarTrac**®**, the window management system for daylighting by Mechoshade™ which recently launch to the market (2009) [Figure **2-2**]. SolarTrac® adjusts shades according to the sun angles, the HVAC system loads and the user-defined direct sun penetration.

A recent study by Tzempelikos (Tzempelikos and Athienitis 2007) presented a simulation study of thermal and daylight conditions with an exterior roller shade for perimeter offices. The south-facing facade, when adjusted for maximum daylight, provided a reduction of 77% in annual electric lighting energy and 16% in cooling energy.

Despite their potential for energy savings, automated systems are still applied rather sparingly in buildings due to their cost and complexity. This research expands on the previous work, by considering multiple cities, control strategies and performance measures.

Fig 2-2: SolarTrac® application (Photo credit: Mechoshade™).

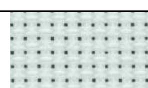
2.3 Energy simulation studies of translucent shades

To understand the impact of translucent shade performance without using room-size instruments and complicated measurements, energy simulation programs can be applied. Moreover, to evaluate the variety and number of currently available glazings and shading systems, simulation tools can help save time.

According to a LBNL study (Jonsson, Lee et al. 2008), though shades appear to be simple and have been widely used for many years, shade fabric optical properties are not accurately characterized. Shade fabric properties are one of the important inputs required in energy simulation programs such as EnergyPlus, DOE-2 and EQuest.

EnergyPlus, the energy simulation software tool used in this study, has the ability to model shades using solar and visible transmittance and reflectance data at normal incidence with an assumption that shades are perfectly diffuse. Shade properties used in this dissertation are as follows [table **2-1**]:

Table 2-1: Shade properties of two shade fabrics, white and dark grey shade (Photo credit: Lutron™).

		Transmittance (τ)	Reflectance (ρ)	Absorptance (α)	openness factor
White shade		0.14	0.71	0.15	0.03
Dark grey shade		0.04	0.05	0.91	0.03

Presently, building energy performance as affected by translucent shades can be predicted using building energy simulation programs such as EnergyPlus, DOE-2 and ESP-r. The programs use a coupled thermal and lighting engine for simulation. The potential of these programs is the ability to perform dynamic shade operation and optimize the energy performance of buildings during the design process, considering site-specific weather data. The programs help to simulate and study the impact of dynamic operation of translucent shades. The approach of using building simulation programs to validate shade performance is very new. There is currently no study reporting the impact of interior translucent shades, their control strategies, and their impact on energy savings and visual quality using simulation tools.

There are some studies on similar shading devices such as exterior roller shades as listed below:

Loutzenhiser (Loutzenhiser, Manz et al. 2007) performed an empirical validation of four energy simulation programs (1)EnergyPlus, (2) DOE-2.1E , (3) TRNSYS-TUD, and (4) ESP-r. The sensitivity analysis of the results with external screens and internal screens were provided. For internal shading screen simulations, EnergyPlus, DOE-2.1E, TRNSYS-TUD, and ESP-r reported mean percentage errors from the simulation results were 6.7%, 13.8%, 5.7% and 4.3% respectively. ESP-r was the only program validated within 95% credible limits. But EnergyPlus showed good credibility at 94%.

Tzempelikos and Athienitis (Tzempelikos and Athienitis 2007) used TRNSYS coupled with EnergyPlus to study the impact of cooling and lighting demand with shading devices on buildings. Exterior translucent shades were used as an example. The simulation results showed that if integrated automatically controlled motorized shading was used in conjunction with a controllable electric lighting system, substantial reduction of energy demand for cooling and lighting could be achieved in perimeter spaces depending on climate and orientation. The study also found that energy and peak demand savings were highly dependent on the control strategy. For window-to-wall ratio (WWR) of 0.3, the use of automatic on/off lighting control can reduce the energy required for lighting by 77% and 16% for cooling.

After reviewing the literature, this thesis proposed to use EnergyPlus as an energy simulation program because it shows good credibility and potential for evaluating translucent shade performance.

2.4 Visual quality

The primary reason to include shading devices on windows is to improve visual quality. Good visual quality can support visual performance and interpersonal communication and improve feelings of well-being which are important to building occupants especially in office environments. There are multiple criteria that must be met for good visual quality. The following criteria and methods are used to qualify and quantify visual quality in this dissertation.

- **Discomfort glare -** Daylight glare index (DGI)
- **Visibility –** Work plane illuminance
- **Task performance -** Luminance ratios
- **Mood and atmosphere -** View

A summary of the indices which can qualify and quantify visual quality of translucent shades is provided. This study uses the daylight glare index (DGI), work plane illuminance, luminance ratios and view.

2.4.1 Daylight glare index (DGI)

Daylight glare index is a metric designed to evaluate lighting under daylight conditions. For daylit rooms, discomfort glare from daylight usually occurs when direct sunlight enters the room and illuminates an interior surface, or when high luminance exterior surfaces, or the sky, are viewed from within. The daylight glare index (DGI) has long been studied (Petherbridge and Hopkinson 1950; Chauvel, Collins et al. 1982; Boubekri and Boyer 1992; Osterhaus 1992). The original form of the discomfort glare constant expressed by Hopkinson, the “Cornell” formula, is the most common form and is used by EnergyPlus. This index, however, tends to overestimate glare under real sky conditions and non-uniform window luminance.

Although DGI results are not yet conclusive, DGI is reported in this study as a means to evaluate one aspect of glare that affects visual quality. According to Chauvel, (Chauvel, Collins et al. 1982) the appropriate index for an office should not exceed 22. The following table **2-2** gives values for glare criteria evaluation based on glare index.

Table 2-2: Glare criteria based on glare index.

Zone	Region	DGI
Discomfort zone	Intolerable	>28
	Just intolerable	28
	Uncomfortable	26
	Just uncomfortable	24
Comfort zone	Acceptable	22
	Just Acceptable	20
	Noticeable	18
	Just perceptible	16

2.4.2 Work Plane Illuminance

For work plane illuminance, daylight factor is a well-known and workable method to measure the relationship between interior and exterior illuminance. However, an idealized overcast sky does not account for realistic conditions.

Nabil and Mardaljelvic (Nabil and Mardaljevic 2005) proposed a new metric to quantify daylight performance called **Useful Daylight Illuminance** (UDI). UDI qualified the interior daylight illuminance under realistic skies in the range of 100-2000 lux as 'useful' based on the behavior of occupants in a daylit office with user-operated shading devices. Values over 2000 lux were suggested as excessive and likely to cause discomfort. The values of work plane illuminance are normally measured at 0.762 m (2.5ft) from the floor on a horizontal plane.

2.4.3 Luminance ratios

A luminance ratio is the ratio of the luminance between a task and its surround. It can be used as an additional measure of visual quality. The IESNA (IESNA 2000) states that luminance ratios generally should not exceed the following recommended ratios for critical work task environments:

Between paper task and adjacent VDT screen	3:1	or	1: 3
Between task and adjacent dark surroundings	3:1	or	1: 3
Between task and remote (nonadjacent) surfaces	10:1	or	1:10

2.4.4 View

It is mentioned in IESNA that "The provision of view to the outside has been suggested to satisfy the workers. The provision of daylight alone (for example, through skylights) will not satisfy a user's desire for view including sky, horizon, and ground. It has been suggested that, to satisfy most workers, windows must cover at least 20% of the window wall area" (IESNA 2000). Translucent shades, when deployed, will block all or some portion of the window. This study only investigates automated control strategies that fully close the shades. To quantify the view impact from translucent shade control strategies, the hourly position of the translucent shade is used.

Only a few studies have been done regarding visual quality indexes for window and shading devices. They are listed as follows:

Carmody (Carmody 2004) reported a visual quality analysis for different types of insulated glazing based on daylight glare index (DGI) and view index. The view index used in the study calculated the portion of window that was obstructed when viewed by occupants.

The study on the New York Times building (Lee and Selkowitz 2006) allowed the interior fabric shades to adjust and admit some daylight penetration at 0.90 m (3ft). Shades were closed when the average window luminance reached 2000 cd/m^2.

Lee and Tavil (Tavil and Lee 2006; Lee and Tavil 2007) showed that applying overhangs with electrochromic glazing significantly reduced the average annual daylight glare index (DGI) and increased annual energy savings for a large window area.

Moeck (Moeck, Lee et al. 1998) used luminance ratios as recommended by IESNA to assess visual quality. By considering the contrast between the task and surrounding view, electrochromic glazings showed increased comfort for critical visual tasks.

2.5 Summary: the gap in the literature

This literature has several gaps in the literature related to translucent shades as follows:

1. Previous studies on translucent shades and windows do not reflect modern shade and glazing characterizations and applications. This research explores more modern shade and glazing selections and applications.

2. Only a few studies addressed interior translucent shades. Despite the potential for energy savings, automated shade and lighting control systems are still applied rather sparingly in buildings due to their cost and complexity. Not all major parameters that impact the energy savings have been explored thoroughly. This research expands on the previous works, by considering factors such as climate, control strategies and performance measures.

3. Detailed simulation studies have not been performed with translucent shades. This thesis will use EnergyPlus as an energy simulation program because it showed good credibility and potential as a tool for evaluating translucent shade performance.

4. The impact of a window and shade combination was previously determined by the use of the solar calorimeter method with real or simulated solar and room-size instruments. These test devices are hard to build and apply, are expensive, very time consuming, and may not provide suitable results for design analysis. A simulation-based approach, as used in this study, provides a better solution for a parametric study of the impact of a shade and window combination.

5. Most of the recent work on visual quality with interior shading devices (Carmody 2004; Tavil and Lee 2006; Lee and Tavil 2007) is focused only on venetian blinds and glazing materials, including electrochromic, but not on translucent shades.

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Chapter 3

SIMULATION

This chapter describes the simulation methodology and is comprised of sections on the simulation parameters, shade control strategies and simulation tools. Simulation parameters and shade control strategies are those used by EnergyPlus, an energy simulation program, to evaluate the energy impacts of translucent shades. Visual quality is evaluated using AGI32 and DAYSIM, lighting simulation programs. The following sections in this chapter discuss the simulation parameters and simulation assumptions, along with the control strategies and analysis methods applied.

3.1 Simulation parameters

This section explains the key simulation parameters in detail and addresses the simulation assumptions used in EnergyPlus.

3.1.1 Climates

Climatic zones are categorized into eight zones for building climatic envelope criteria according to ASHRAE (ASHRAE 2005). Building construction and systems generally vary based on the recommendations for each climatic zone. This study applies five different locations [Figure **3-1**] as follows:

Cooling-dominated climates:
- Phoenix, Arizona
- Houston, Texas

Heating-dominated climates:
- Philadelphia, Pennsylvania
- Minneapolis, Minnesota
- Seattle, Washington

These locations were chosen to be representative of different climates and daylight availability present in North America. Details of the thermal and daylighting characteristics for these climates are shown in table **3-1**.

Fig 3-1: Five different cities of various climatic zones and sky types present in North America.

Table 3-1: Climate thermal and daylighting characteristics for the test cases.

Region	Heating Degree Days	Cooling Degree Days	Heating Design temperature, ºC (ºF)	Cooling Design temperature, ºC (ºF)		Annual Cloudiness (number of days)		
	HDD65	CDD50	99.5%	Dry-Bulb 1%	Wet-Bulb 1%	Clear	Partly Cloudy	Cloudy
Houston (2A)	1599	6876	-2.8 (27)	34.4 (94)	25 (77)	90	114	161
Phoenix (3B)	1350	8425	2.8 (37)	42 (108)	21 (70)	211	85	70
Philadelphia (4A)	4954	3623	-11.7 (11)	31.7 (89)	23.3 (74)	93	112	160
Seattle (5B)	4908	2021	-5.0 (23)	27.2 (81)	17.8 (64)	71	93	201
Minneapolis (6A)	7981	2680	-26.7 (-16)	31 (88)	21.7 (71)	95	101	169

Weather data for these five cities were obtained from typical meteorological year 2 data (TMY2) with the test reference year of 2002. Although there is currently a newer weather data set, TMY3, which represents weather data during the period 1991-2005, these data are still in the early stages of use and contain some incorrect illuminance and luminance values. Hence, the TMY2 [Table **3-2**] were used in this dissertation.

3.1.2 Building geometries, building zones and orientations

Two hypothetical building geometries with test spaces on each orientation were used as representative test cases. The study includes the impact of shade control strategies on building level results and later focuses more on the room level for perimeter zones facing each of the standard compass directions.

Table 3-2: Site information and the TMY2 reference numbers.

Region	Latitude	Longitude	Time zone	Daylight saving time (DST)	Magnetic declination	TMY2 ref. no.
Houston, TX	29.97 N	95.37 W	GMT -6 (Central)	Yes	4°-19’ E	12960
Phoenix, AZ	33.42 N	112.02 W	GMT -7 (Mountain)	No	11°-52’ E	23183
Philadelphia, PA	39.87 N	75.25 W	GMT -5 (Eastern)	Yes	12°-10’ W	13739
Seattle, WA	47.45 N	122.3 W	GMT -8 (Pacific)	Yes	18° 16' E	24233
Minneapolis, MN	44.87 N	93.22 W	GMT -6 (Central)	Yes	1°-42’ E	14922

1) Square floor plan

A hypothetical one-story office building of 1,487 m^2 (16,000 ft^2) with a 929 m^2 (10,000 ft^2) central core zone was considered, see figure **3-2**. The core zone is surrounded by four identical perimeter zones of 30.5 m (100 ft) by 4.6 m (15 ft). Each perimeter zone has private offices of 3.0m x 4.6m (10 ft x 15 ft) with a ceiling height of 3.2 m (10.5 ft) and a roof height at 3.7 m (12 ft), ceiling/wall/floor reflectances of 80/60/30, and an exterior ground reflectance of 20% with two separate window-to-wall area ratios of 0.20 and 0.40. [Figure **3-4**]. The roof and floor surface are adiabatic so the results apply to an intermediate floor in a multi-story building.

2) Long thin building with two orientations

The long façades for this building are considered to face both North-South (N-S) and East-West (E-W). This is a theoretical one-story office building of 1,820.7 m^2 (19,597.8 ft^2) with a 886.35 m^2 (9540.95 ft^2) core zone and 934.37 m^2 (10,057.47 ft^2) perimeter zones as shown in figure **3-3**. The building length is 3.28 times longer than the square building. The perimeter zones are 90.62 x 4.6 m (297.3 x 15 ft) and 20.09 x 4.6 m (65.9 x 15 ft). The perimeter rooms on all four facades are identical in size and reflectance to those in the square building. Each perimeter zone is comprised of private offices of 3.0m x 4.6m (10 ft x 15 ft) with a ceiling height of 3.2 m (10.5 ft) and a roof height at 3.7 m (12 ft) with ceiling/wall/floor reflectances of 80/60/30, and an exterior ground reflectance of 20% with window-to-wall area ratios of 0.20 and 0.40 as shown in figure **3-4**. The interior walls are adiabatic. The roof and floor surface are also adiabatic.

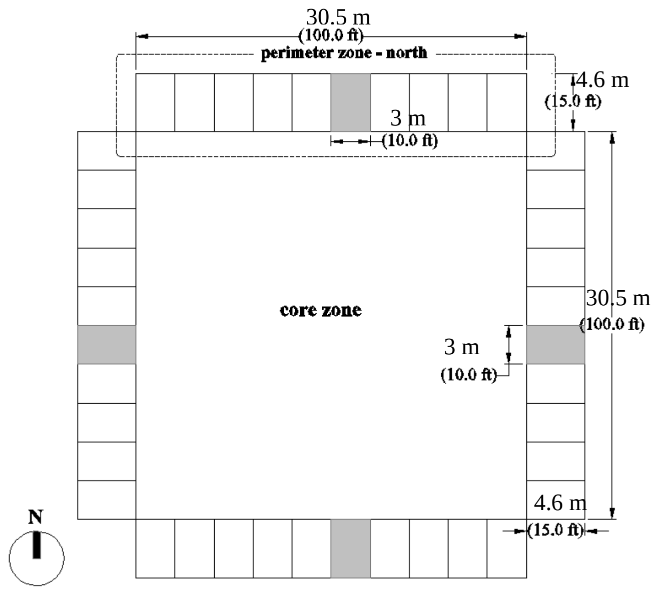

Fig 3-2: Square floor plan building of 1,487 m^2 (16,000 ft^2).

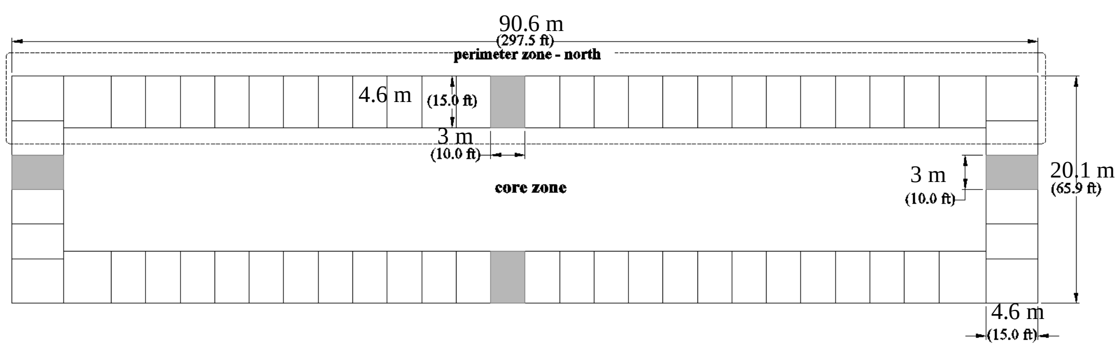

Fig 3-3: Long thin building of 1,519 m^2 (16,350 ft^2) facing (N-S).

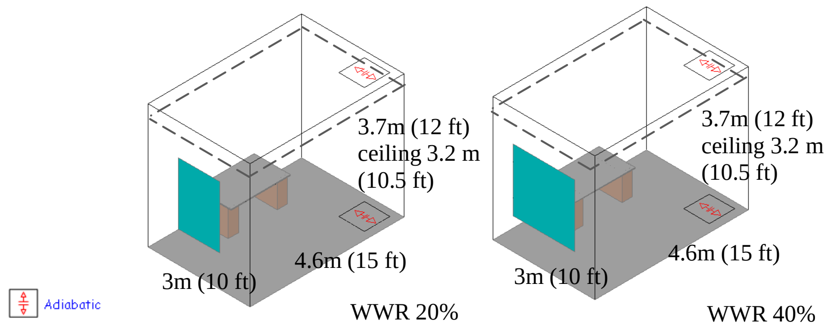

Fig 3-4: Test spaces show different window-to-wall area ratio, 0.20 and 0.40, and adiabatic surfaces.

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3.1.3 Building Descriptions

The calculation of building heat gain and loss can be achieved through analysis of the building envelope. To represent general commercial buildings in North America, this study used building materials and construction that complied with ASHRAE/IESNA Standard 90.1-2004 as shown in Table **3-3**.

The heating ventilation and air-conditioning system (HVAC) and lighting system are important factors in building design because they directly affect energy consumption.

For the HVAC system, this study uses the simple 'Purchased Air' object in EnergyPlus as an ideal variable-air-volume (VAV) terminal unit. A purchased-air object supplies cooling or heating to a zone in sufficient quality to meet the zone loads. The input is specified by the supply air condition. Both heating and cooling systems use electricity. The heating thermostat was set at 13°C (55°F) at night and 23°C (73.4°F) during occupied hours. The cooling thermostat was set at 35°C (95°F) at night and 21°C (70°F) during occupied hours.

Table 3-3: ASHRAE 90.1-2004 insulation values used in this study.

Region	Walls		Roof		Floors		Ref.
	Insulation min. R-Value, $m^2 \cdot K/W$ ($h \cdot ft^2 \cdot °F/Btu$)	U-factor, W/m^2K (Btu/h-ft^2-°F)	Insulation entirely above deck min. R-Value, $m^2 \cdot K/W$ ($h \cdot ft^2 \cdot °F/Btu$)	U-factor, W/m^2K (Btu/h-ft^2-°F)	Insulation min. R-Value, $m^2 \cdot K/W$ ($h \cdot ft^2 \cdot °F/Btu$)	U-factor, W/m^2K (Btu/h-ft^2-°F)	Std. 90.1-2004 Table no.
Houston (2A)	frame wall 2.3 (R-13)	0.44 (0.08)	2.64(R-15 c.i.)	0.38 (0.07)	0.74 (R-4.2 c.i.)	1.35(0.24)	5.5-2
Phoenix (3B)	1.0 (R-5.7 c.i.)	1.00 (0.18)	2.64(R-15 c.i.)	0.38 (0.07)	1.1 (R-6.3 c.i.)	0.9 (0.16)	5.5-3
Philadelphia (4A)	1.0 (R-5.7 c.i.)	1.00 (0.18)	2.64(R-15 c.i.)	0.38 (0.07)	1.1 (R-6.3 c.i.)	0.9 (0.16)	5.5-4
Seattle (5B)	1.3 (R-7.6 c.i.)	0.75 (0.13)	2.64(R-15 c.i.)	0.38 (0.07)	1.1 (R-6.3 c.i.)	0.9 (0.16)	5.5-5
Minneapolis (6A)	1.7 (R-9.5 c.i.)	0.60 (0.11)	2.64(R-15 c.i.)	0.38 (0.07)	1.5 (R-8.3 c.i.)	1.37(0.12)	5.5-6

Note: c.i. means continuous insulated

For a lighting system, the test space used linear fluorescent fixtures with a direct-indirect distribution. The power density of electric light in the test space was 9 W/m^2 (0.9 W/ft^2).

For the lighting control system, the test cases considered no dimming control and a system with dimming control. The dimming control system is continuous/off dimming with performance as shown in figure **3-5**. Lights are switched off completely when the minimum dimming point is reached. The minimum input power fraction is set at 0.1, which means 10% of full power (9 W/m^2) is applied at 2% light output just before the lights are switched off.

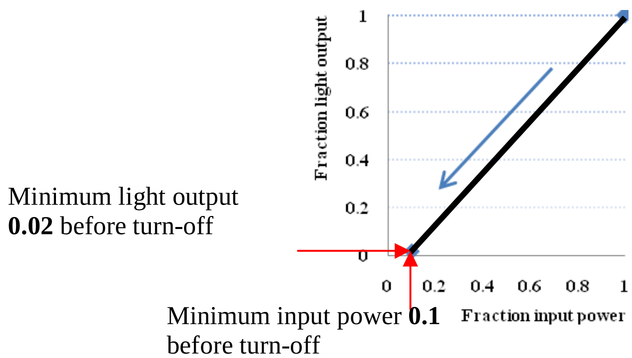

Fig 3-5: Power vs. light output for the continuous/off dimming system.

Building occupancy schedules for this study are that of a commercial building which is assumed to be occupied from 7 AM to 7 PM on weekdays. Both HVAC and lighting systems follow this schedule. Daylight savings time lasts from March 10th to November 2nd.

Window area is based on window-to-wall ratios (WWR) of 20% and 40% as recommended from ASHRAE standard 90.1-2004 for these test locations (table 3-4). Window assemblies are a 1.5" (0.03 m) aluminum frame window with thermal bridging and window areas as shown in figure **3-6**.

1) WWR 20% - 1.2 m x 1.8m, 0.9 m from the floor (4 ft by 6 ft, and 3 ft from the floor)
2) WWR 40% - 2.4 m x 1.8m, 0.9 m from the floor (8 ft by 6 ft, and 3 ft from the floor)

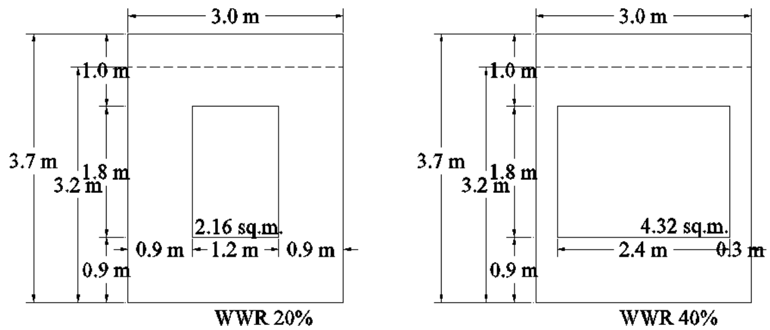

Fig 3-6: Window areas for the test spaces.

Basic glazing properties that quantify the energy performance are solar heat gain coefficient (SHGC), thermal transmission (U-factor), visible transmittance (Tvis), and air leakage. The ASHRAE recommended glazing values for SHGC and U-factor are presented in table **3-4**.

Table 3-4: Vertical glazing requirements for a non-residential building.

City	WWR	Assembly Max U-factor/ Fixed window, W/m^2-K ($Btu/hr\text{-}ft^2$-F)	Assembly SHGC (All orientations / North-oriented)	ASHRAE Table No.
Houston, TX	0.20	3.20 (0.57)	0.25 / N-0.49	5.5-2
	0.40	3.20 (0.57)	0.25 / N-0.39	
Phoenix, AZ	0.20	6.85 (1.22)	0.39 / N-0.61	5.5-3
	0.40	6.85 (1.22)	0.34 / N-0.61	
Philadelphia, PA	0.20	3.20 (0.57)	0.39 / N-0.49	5.5-4
	0.40	3.20 (0.57)	0.39 / N-0.49	
Seattle, WA	0.20	3.20 (0.57)	0.39 / N-0.49	5.5-5
	0.40	3.20 (0.57)	0.39 / N-0.49	
Minneapolis, MN	0.20	3.20 (0.57)	0.39 / N-0.49	5.5-6
	0.40	3.20 (0.57)	0.39 / N-0.49	

The SHGC and U-factor of the windows and shades used in this study are presented in table 3-5. Compliant windows with and without a low emission (low-E) coating meet ASHRAE 90.1-2004 requirements for all climates tested [table **3-4**]. The non-compliant double clear glazing, window A, represents a commercially available and popular choice in older current commercial buildings. Considering non-compliant windows in existing buildings is a worst case condition because of their poor energy performance. Visible transmittance (Tvis) of the three compliant double pane glazings, window B, C, D and the non-compliant double pane glazing, window A, range from 0.48-0.80. The visible transmittances of the dark and light shades applied in this study are 0.04 and 0.14 respectively. Visible reflectances are as shown in table **3-5**.

The use of translucent shades can alter the overall window optical properties, hence, the window and shade combination, as determined by EnergyPlus, are used in simulations when shades are deployed.

Table 3-5: Window and translucent shade solar, optical and thermal properties use in this study.

Window and shade properties	SHGC	Tvis	ρ (rho)	U-factor, W/m^2-K (Btu/hr-ft^2-F)
Window A – Double clear with air gap	0.708	0.790	0.15	2.68 (0.477)
Window B – Double pane tint with air gap (cold climate compliance)	0.379	0.603	0.11	2.73 (0.479)
Window C - Spectral selective low-E (2) with air gap (hot climate compliance)	0.239	0.609	0.33	1.62 (0.288)
Window D - Spectral selective low-E (2) with air gap (hot / cold climate compliance)	0.279	0.642	0.12	1.61(0.284)
White shade	*	0.14	0.71	*
Dark grey shade	*	0.04	0.05	*

Note: * means no data available

The performance of the glazings can be evaluated using the light-to-solar gain ratio (LSG). LSG for this study is defined in figure **3-7** below. A higher visible transmittance and lower solar heat gain coefficient is preferred for a hot climate while the slightly higher solar heat gain coefficient is acceptable in a cold climate. This study assumes low air leakage (zero) due to the use of fixed windows.

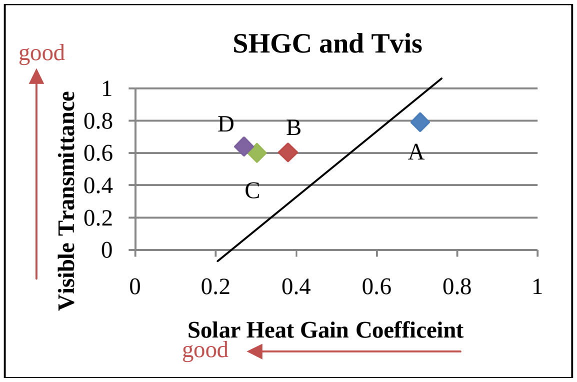

Fig 3-7: Solar heat gain coefficient and visible transmittance for glazings in this study

Translucent shades are assumed to be perfect diffusers, i.e., Lambertian, in EnergyPlus. This means direct radiation that falls upon a shade is reflected and transmitted as hemispherically uniform diffuse radiation with no direct component of transmitted radiation. Shade properties, like transmittance (τ), reflectance (ρ) and absorptance (α), are the same for the front and back of the shade and are independent of its incident angle. Shades cover the inside of the windows excluding the frame portion. The distance and the end condition (i.e. sealed, unsealed) between the shades and glass/frame can be set. A 25 mm (1 in.) insulating glass unit comprised of two 6 mm (0.25 in.) panes with an air gap of 13 mm (0.5 in.) was used. Shades are hung inside at a distance of 38.1 mm (1.5 in.) from the window with the side track unsealed.

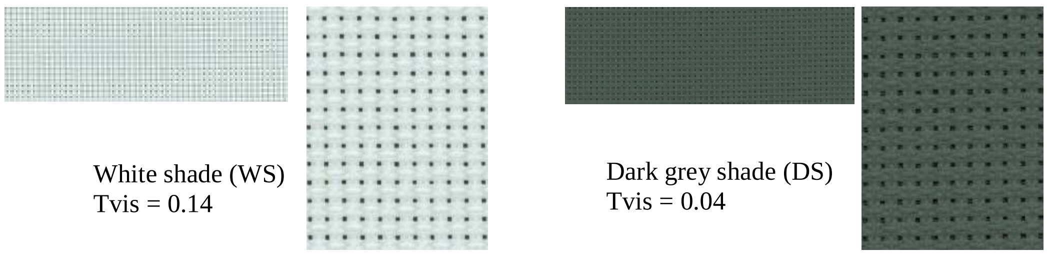

Fig 3-8: Translucent shade fabrics (Photo credits: Lutron™).

The translucent shade fabrics used [figure **3-8**] are white and dark grey in color with an openness factor of 0.03. The 0.03 openness factor means that 3% of the fabric for a straight-on viewing area is perforated. The physical properties of each shade are reported in table 3-5. The white shades represent high transmittance shade values while the dark grey shades represent low transmittance shade values. According to the manufacturer's data (Lutron 2009), shades with an openness factor of 0.03 have a high transmittance value of 0.15 and a low transmittance value of 0.02. So the selection of these two shade colors roughly represents the extremes of shade transmittance commonly found in the market.

3.2 Shade Control Strategies

Different shade control strategies and lighting control systems are defined and analyzed with both the white and dark shades; denoted (*WS* and *DS*), to determine their impact on heating, cooling and lighting energy use. This thesis compared annual heating, cooling and lighting energy savings and visual comfort to a base case (*NS*) that assumed no shade or lighting control (the electric lights were always on).

Shades can be controlled in EnergyPlus as "open" or "closed". The choices for controlling the shades are based on the following shading control inputs in EnergyPlus.

1. Static control
    - AlwaysOn: Shading is always closed.
    - AlwaysOff: Shading is always open.
2. Schedule control

- OnIfScheduleAllows: Shading is on if schedule value is non-zero.

3. Solar radiation incident on the window control
   - OnIfHighSolarOnWindow: Shading is on if solar radiation incident on the window exceeds a setpoint value(W/m^2)

These shading control types are then developed into shade control strategies investigated throughout this dissertation. These shade control strategies are composed of one basic and five automatic control strategies as listed below:

3.2.1 Control Strategies

One shade control strategy assumes the shades are fully closed at all times which represents a worst case scenario, where the occupant closes the shade, then does not adjust it. The control strategies are summarized as follows.

Static control condition

- **Shade closed all day (*DN*):** This control places the shades in a fully closed position (down) all day. This test cases includes cases in which lighting control is both activated and not activated. When lighting control is in use, the name of the control has *_ctr* following the name (*DN_ctr*). A test for seasonal control that leaves shades open during the winter months (October to March) and closed during summer months (April to September) without lighting control is also considered (*DN_summer*). This basic control is not a proposed strategy but analyzed for the benefit of comparison.

Automatic control strategies

The goal of the automatic control strategies is to maximize energy savings along with the visual comfort of the occupants. The automatic control strategies are always applied with lighting control (*_ctr*). These control strategies are configured as either fully open or fully closed at a point in time based on setpoint criteria:

- **Time of day control (*EMWA_ctr*):** With this test control strategy**,** shades are activated on the east façade in the morning (7am-1pm DST), the west façade in the afternoon (1pm-7pm DST), with no shading on the north, and all-day shading on the south façade. The reason for applying time schedule control is to maximize the lighting energy savings during the time that sunlight is not shining directly onto the window.
- **Solar Radiation control (*SolXXX_ctr*):** The shades are dropped when the total solar radiation incident on the windows reaches a certain setpoint.

  (1) Low solar setpoint: (*Sol189*) 189 W/m^2 (60 $Btu/hr\text{-}ft^2$),

  (2) Medium solar setpoint: (*Sol378*) 378 $Btu/hr\text{-}ft^2$ (40$Btu/hr\text{-}ft^2$)

  (3) High solar setpoint: (*Sol630*) 630 W/m^2 (200 $Btu/hr\text{-}ft^2$).

- **Sunlight penetration control (*A_pA_z_ctr*):** This method controls the shades so no direct sunlight penetrates beyond a 0.6m (2ft) distance. Shades are fully closed when the profile angle (A_p) is between 0 and 72 degrees and the building elevation azimuth angle (A_z) is less than 67 and 72 degrees for WWR 0.20 and 0.40 respectively [Figure **3.9**], regardless of cloud cover condition.
- **Direct normal illuminance control** (***DIR2500_ctr* and *DIR5000_ctr*):** These control strategies adjust the shades based on sunlight penetration, as in A_pA_z control, but open the shades when the direct normal exterior illuminance is below 2500 lux (*DIR2500_ctr*) and 5000 lux (*DIR5000_ctr*) respectively, as the sky conditions approach overcast.
- **Work plane illuminance control (*Ewp_ctr*):** This control strategy applies the shades to reduce daylight levels within the space when the interior illuminance exceeds 2000 lux at the critical work plane point.

All these control strategies are hypothetical control strategies which can be applied in real systems with an appropriate sensing device and controller.

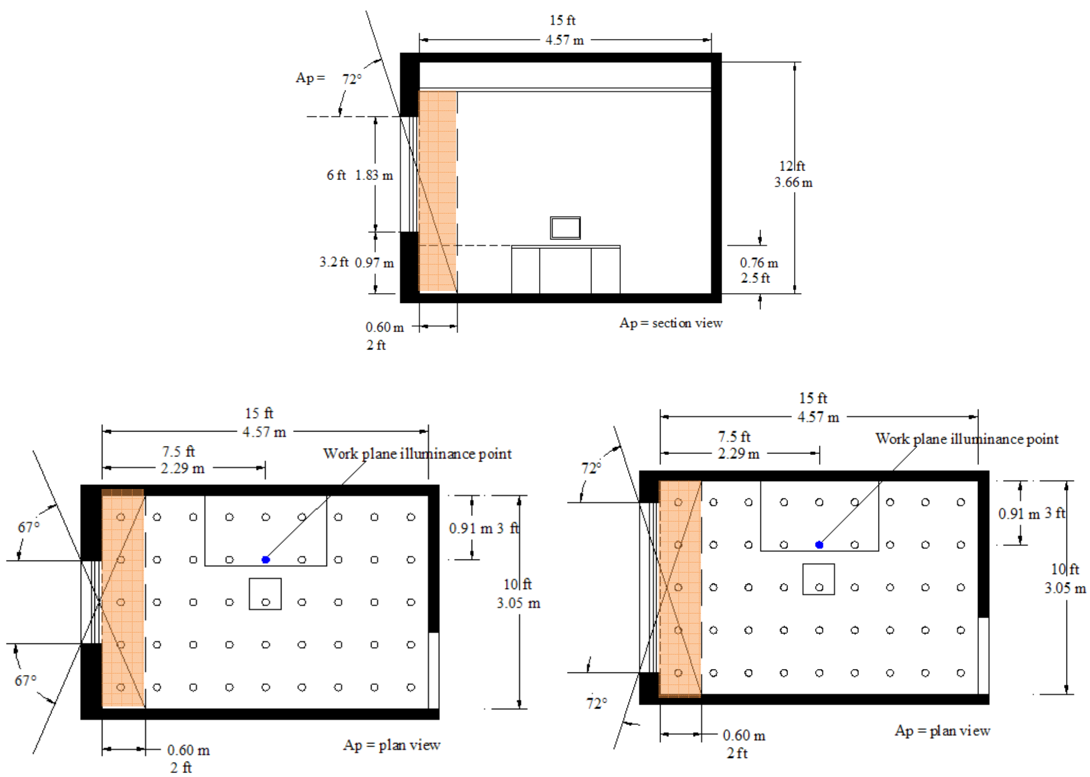

Fig 3-9: Profile angle (A_p) (above), and solar elevation azimuth angle (A_z) (below) dictate shade position (shaded area) for WWR=0.20 (below left) and 0.40 (below right).

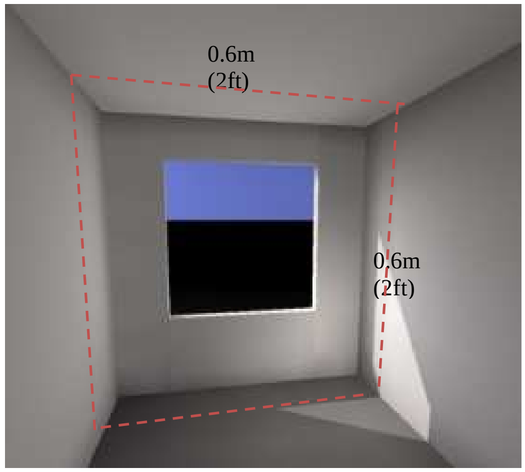

Fig 3-10: Rendered image shows maximum 0.6m (2ft) allowable sunlight penetration zone (WWR = 0.40).

3.3 Simulation Tools

3.3.1 EnergyPlus

EnergyPlus, a whole building energy simulation program, is used in this study to assess the potential energy savings of different shade control strategies. EnergyPlus reports the energy results as hourly, monthly and annual energy loads for total, heating, cooling and lighting energy for a designated space or zone.

EnergyPlus is a simulation program designed for modeling buildings with all their associated heating, ventilating, and air conditioning equipment. Heating, cooling and lighting energy savings are determined from the annual hourly energy loads for the test spaces. It models translucent shades by using window heat balance and daylighting calculations.

The window and shade thermal model accounts for the thermal interactions between the shading layer and the adjacent glass.

An important feature of the shading device thermal model is that it calculates the natural convective airflow between the shading device and the glass. This flow affects the temperature of the shading device and glazing and, for interior shading, is a determinant of the convective heat gain from the shading layer and glazing to the zone air. The airflow model is based on the ISO standard 15099, “Thermal Performance of Windows, Doors and Shading devices - Detailed calculations” (ISO 2003). The following are considered by the shading device thermal model during simulations:

- The long-wave radiation (IR) from the surround absorbed by the shade

- Inter-reflection of IR between shade and glass
- Direct and diffuse solar radiation absorbed by the shade
- Inter-reflection of solar radiation between shade and glass
- Convection from shading layer and glass to zone air
- Natural convection airflow in the gap between shade and glass induced by buoyancy effect to zone air

The model assumes that shades cover the glazed part of the window and are parallel to the glazing. The shading layer is separated from the glazing by an air gap and does not cover the frame part of window.

The heat balance calculation for a window and shade does not use the single U-factor directly. EnergyPlus calculates nominal U-factors for reporting, but when the simulation runs they are constantly being calculated for current conditions/ timesteps using physical properties. This is because the heat balance results depend on the natural convective airflow between the shade and glass which in turn is highly dependent on window height and other parameters that are not part of the construction definition.

The detailed method is described in the EnergyPlus engineering reference in the "Window heat balance calculation" section (DOE 2007). The calculation can be applied to different types of glazing such as glazing systems with two glass layers and interior shading.

The daylighting calculation uses solar and visible transmittance and reflectance data at normal incidence with an assumption that the shades are flat, perfectly diffuse, and cover all parts of the window, excluding the frames. Shades are controlled by the control strategies previously described.

EnergyPlus daylighting simulations are based on the predecessor program, DOE 2-1 (Winkelmann and Selkowitz 1985). It calculates daylight factors for four Perez sky types and a series of sun positions covering the range of solar altitude and azimuth at the specific building latitude. These factors are then used to determine the interior illuminance level at the reference points within a zone/space. The electric lighting control system is simulated to determine the lighting energy needed to make up the difference between the daylighting illuminance and the design illuminance. Finally, the zone/space electric lighting reduction factor is passed to the thermal calculation, which uses this factor to reduce the heat gain from lights.

The direct component of interior daylight illuminance is calculated by subdividing windows into small grids and finding the direct flux contribution from a window element reaching a reference point without interior reflection. The net direct horizontal illuminance is the sum of all window elements above the work plane. The internally reflected component is calculated using the split-flux method to arrive at the interior daylight illuminance. The split-flux method considers daylight transmitted by a window split into two parts - a downward-going flux and an upward-going flux which are divided by the imaginary horizontal plane passing through the center of the window (window midplane) [figure **3-11**]. Each portion of the flux is then absorbed by the room surfaces.

The average reflectance of the walls and floor and the walls and ceiling below and above the window midplane are used for the downward and the upward flux respectively.

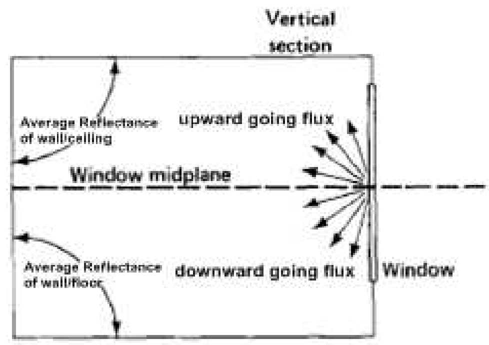

Fig 3-11: Vertical section showing upward and downward going transmitted fluxes in split flux calculation of the internally reflected component of interior illuminance.

The analysis addresses work plane illuminance and glare index at a single reference point within the test space [figure **3-12**] with the glare point viewing the window directly. Lighting energy savings are also determined using the single reference point.

The lighting energy is then calculated from how much lighting energy is needed to satisfy an illuminance of 500 lux (50 fc) at the reference point. Work plane illuminance was measured at a height of 0.762 m (2.5ft).

Daylight glare index (DGI) is presented as hourly data. This calculation assumes a worst case scenario where the occupants sit at the work plane illuminance reference point in figure 3-8 and view the window directly at a height of 1m (3.5ft). A position where the occupant faces the window, however, would not represent good office planning. The threshold of a "just comfortable" condition is 22, so values greater than 22 are considered to be objectionable.

The system's performance related to the view of the exterior is determined by the number of hours when the shade is used based on the shade control strategy.

Since EnergyPlus is not capable of analyzing luminance ratios within the test spaces, AGI32 and DAYSIM (lighting simulation programs) were used for further analysis.

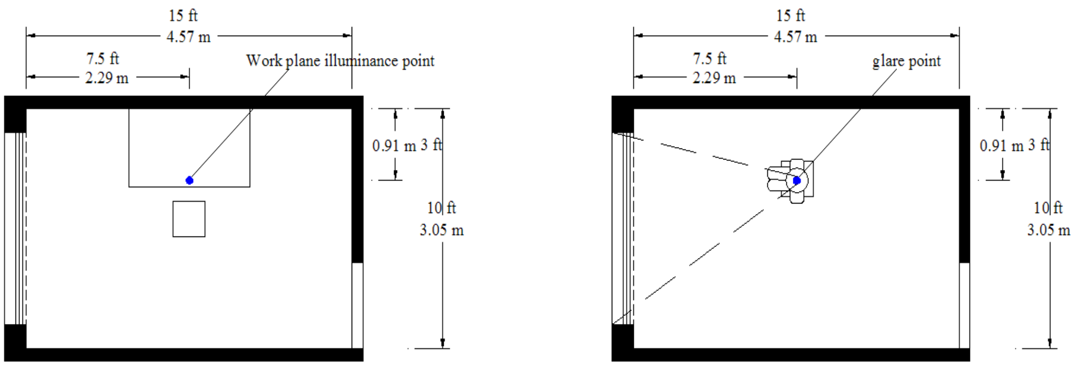

Fig 3-12: Work plane illuminance point at 0.762m (2.5ft) height (left) and glare point at 1m (4ft) height (right) within the test space.

3.3.2 AGI32

AGI32 is a lighting simulation program that employs a radiosity calculation for determining illuminance and luminance levels. The sky conditions used in the program are based on CIE sky conditions. In this work, luminance ratios were studied by modeling a test space with a clear window, as well as windows with both white and dark shades which were assumed to be Lambertian, to obtain these ratios.

Luminance ratios are ratios of luminance values between a task and its surrounding surfaces, which are used as an additional measure of visual quality. The IESNA states that luminance ratios generally should not exceed the following recommended ratios for critical work task environments:

Between paper task and adjacent VDT screen	3:1 or 1:3
Between task and adjacent surroundings	3:1 or 1:3
Between task and remote (nonadjacent) surfaces	10:1 or 1:10

The model and location of the luminance ratio measurement points are shown in figure **3-13**.

Two primary tasks were analyzed, a paper task and the VDT (Video Display Terminal unit). For the VDT, an average luminance of 200 cd/m^2 was considered for the self-luminous monitor.

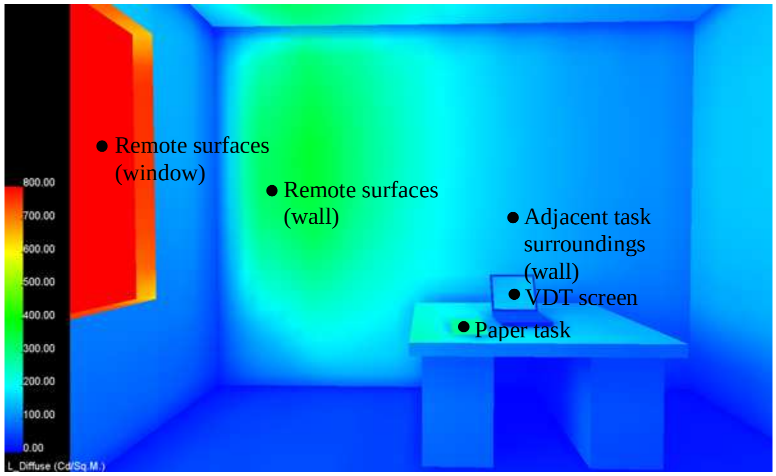

Fig 3-13: Measurement points for the luminance ratio analysis for AGI32.

3.3.3 DAYSIM

DAYSIM is a daylight simulation program that employs the daylight coefficient method and uses the Perez all-weather sky model in daylighting calculations. The program's lighting calculations are based on RADIANCE which uses a raytracing algorithm. DAYSIM was also applied to evaluate luminance ratios in relation to recommended values the same as AGI32. All surfaces were assumed to be Lambertian (perfectly diffuse).

The illuminance values are measured at the measurement points. Luminance values are obtained from equation **3-1**:

$$L = (E*\rho) / \pi \qquad [3\text{-}1]$$

Where:

L	=	Luminance at the reference point [cd/m^2]
E	=	Illuminance at the reference point [Lux]
P	=	Surface reflectance
π	=	pi value [3.412]

Average Window Luminance

Average window luminance [cd/m^2] is adapted from methodology described by Littlefair, Aizlewood and others (Littlefair, Aizlewood et al. 1994). The methodology suggests the use of a shielded cone with a matte black surface (reflectance =0) on the illuminance sensors that view the entire window without direct sun influence as shown in figure **3-14**.

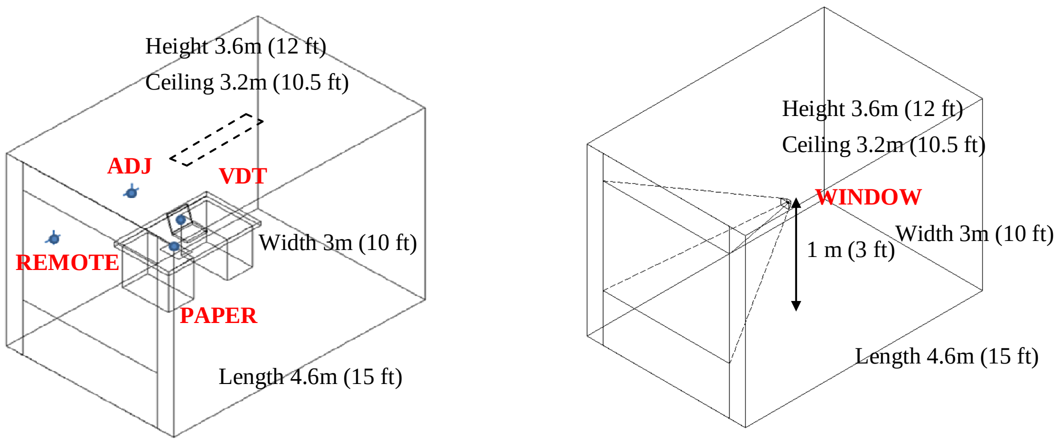

Fig 3-14: Location of illuminance sensors (left) and a shielded illuminance sensor (right) that are used to compute room surface luminances.

The average window luminance is calculated from the following equation **3-2**:

$$L_s = \frac{E_{shielded}}{\pi * C_{win \rightarrow pt}} \quad [3\text{-}2]$$

Where:

L_s	=	the average window luminance [cd/m^2]
$E_{shielded}$	=	Average vertical illuminance from shielded illuminance sensor [lux]
$C_{win \rightarrow pt}$	=	Configuration factor of window to the shielded illuminance sensor
π	=	pi value [3.412]

3.4 References

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Chapter 4

SIMULATION RESULTS

This chapter evaluates and analyzes the impact of translucent shades upon total, heating, cooling and lighting energy use and savings when automatic shade control strategies are applied. The analysis starts at the **building level** and later focuses more on the **space level**. This chapter also includes energy performance analysis of different basic shade control and automatic shade control strategies with a focus on **maximizing energy savings** by minimizing heating, cooling and lighting energy use. Automatic shade control strategies that focus more on energy savings while providing acceptable visual quality are addressed in the next chapter.

4.1 Shade control strategies to maximize total energy savings

Automatic control strategies are developed for further analysis of how shades can be controlled in a building. The following control strategies are tested against various building parameters.

- A time of day control strategy (*EMWA_ctr*) represents a simple idea of shade use to maximize lighting energy savings during the time that sunlight could not shine directly onto a window. Shades can be left open all day on the north facade, closed in the morning on an east façade; then opened; and closed only in the afternoon on a west façade; and completely close on the south façade.

- A solar set point control strategy (*Solxxx_ctr*) develops from the concept of using the amount of solar radiation to regulate shade use. This concept is previously found in the electrochromic glazings and blinds research by Sullivan, Lee and others (Sullivan, Lee et al. 1994).

To provide a comparison with more simple shade control types, the following simple shade controls are also presented.

- A shade closed all day (*DN*, *DN_ctr*) approach represents simple shade control behavior normally found in office buildings with manually-operated shades. When occupants close shades, they normally leave them closed without changing them back, sometimes for the whole year as a worst case scenario. Automatic lighting control (dimming) (*DN_ctr*) is also added to this case to determine the impact of manually-operated shades with a lighting control system.

The results of each combination of shade control strategy and lighting control are presented in the following sections.

4.2 Building level results

This section addresses annual total energy savings on the building level for two different geometries: **a square building**, **a long thin building** with the long exposures facing north-south **(N-S),** and **a long thin building** with the long facades facing east-west **(E-W)**. The impacts upon the **core** and the **perimeter zones** at the building level are reported seperately. The closed all day shade control strategy is applied with and without lighting control (***DN, DN_ctr***). The goal is to determine the impact of shades as it would occur in **an existing building** with standard double-clear windows (**Window A**; SHGC=0.70/ U=2.68/ Tvis=0.79) with **WWRs** of **0.20** and **0.40**, and two different shade colors **-** white (**WS**) with a high transmittance (Tvis =0.14) and dark shades (**DS**) with a low transmittance (Tvis = 0.4). The base case is the case without shades (***NS***), which is normally used in building simulations during preliminary building design. These test cases were performed for five different climates: Minneapolis (**MN**), Philadelphia (**PA**), Seattle (**WA**), Houston (**TX**) and Phoenix (**AZ**).

4.2.1 Impact of shades closed all day (*DN*)

Tables **4-1** and **4-2** report the impact of shades on total energy savings with the shade closed all day. Since lighting loads are equal in all cases in this section due to no savings from lighting control systems, the differences in results are due to building heating and cooling loads. The detailed total energy use per building area are reported in these tables for the square, long thin N-S and long thin E-W geometries with WWR of 0.20 and 0.40 respectively in appendix **A-1** through **A-2.**

Shade properties, building geometry, climate and window area

The results show that when applying shades to an existing building, white shades perform better than dark shades, in general, in all climates and across different WWRs.

With white shades, the long thin E-W building shows the highest total energy savings. The square building and the long thin N-S building present lower savings in all climates except for WWR=0.40 in Minneapolis where using a white shade presents an increase in total energy compared to dark shades.

Table 4-1: Total energy savings on different building geometries in cold climates, MN, PA and WA, with shades closed all day and no lighting control (*DN*) and WWR of 0.40. A negative percentage represents an increase in the energy required (window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79).

WWR 0.40		PA		MN		WA		TX		AZ	
		DN_ WS	*DN_ DS*	*DN_ WS*	*DN_ DS*	*DN_ WS*	*DN_ DS*	*DN_ WS*	*DN_ DS*	*DN_ WS*	*DN_ DS*
Square	Heating	-3.48%	0.38%	-3.16%	0.70%	-3.56%	0.69%	-1.00%	0.01%	-0.59%	-0.08%
	Cooling	7.02%	-0.61%	4.68%	-0.36%	6.35%	-1.08%	9.59%	-0.31%	10.8%	0.12%
	Total	**3.53%**	-0.23%	**1.52%**	0.34%	**2.78%**	-0.39%	**8.59%**	-0.30%	**10.3%**	0.04%
Longthin N-S	Heating	-4.57%	0.18%	-4.29%	0.58%	-4.44%	0.63%	-1.40%	0.17%	-0.67%	-0.11%
	Cooling	7.77%	-0.47%	5.03%	-0.24%	6.92%	-0.86%	9.77%	-0.34%	11.7%	0.49%
	Total	**3.20%**	-0.30%	**0.74%**	0.34%	**2.47%**	-0.22%	**8.37%**	-0.18%	**11.0%**	0.38%
Longthin E-W	Heating	-3.82%	0.31%	-3.41%	0.65%	-3.99%	0.61%	-1.22%	0.20%	-0.68%	-0.12%
	Cooling	8.99%	-0.26%	6.19%	-0.17%	8.36%	-0.92%	11.4%	-0.09%	13.4%	0.69%
	Total	**5.17%**	0.05%	**2.78%**	0.49%	**4.37%**	-0.31%	**10.2%**	0.12%	**12.8%**	0.57%

Table 4-2: Total energy savings on different building geometries in cold climates, MN, PA and WA, with shades closed all day and no lighting control (*DN*) and WWR of 0.20. A negative percentage represents an increase in the energy required (window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79).

WWR 0.20		PA		MN		WA		TX		AZ	
		DN_ WS	*DN_ DS*	*DN_ WS*	*DN_ DS*	*DN_ WS*	*DN_ DS*	*DN_ WS*	*DN_ DS*	*DN_ WS*	*DN_ DS*
Square	Heating	-2.35%	0.13%	-2.07%	0.23%	-2.53%	0.22%	-0.77%	-0.1%	-0.50%	-0.1%
	Cooling	3.73%	0.08%	2.48%	0.05%	3.16%	-0.3%	5.57%	0.26%	6.40%	0.51%
	Total	**1.38%**	0.21%	**0.41%**	0.28%	**0.64%**	-0.1%	**4.80%**	0.23%	**5.90%**	0.43%
Longthin N-S	Heating	-3.05%	0.06%	-2.70%	0.18%	-3.05%	0.22%	-0.96%	0.06%	-0.72%	0.00%
	Cooling	3.92%	0.12%	2.55%	0.08%	3.34%	-0.2%	5.51%	0.11%	6.31%	0.43%
	Total	**0.87%**	0.18%	-0.15%	**0.3%**	**0.29%**	0.04%	**4.55%**	0.17%	**5.59%**	0.43%
Longthin E-W	Heating	-2.54%	0.11%	-2.23%	0.23%	-2.86%	0.17%	-0.84%	0.09%	-0.61%	0.04%
	Cooling	4.84%	0.23%	3.29%	0.15%	4.15%	-0.2%	6.66%	0.34%	7.70%	0.68%
	Total	**2.30%**	0.34%	**1.06%**	0.38%	**1.29%**	-0.1%	**5.82%**	0.42%	**7.09%**	0.72%

The hot climate cities exhibit higher total energy savings than the cold climate cities. This is because of an increase in heating energy required in the cold climates and the higher cooling energy required in the hot climates.

The highest **total energy savings** (bold values in tables **4-1** and **4-2**)**,** compared to the base case, occurred when shades are used in a **hot climate**.

For a larger window area, WWR=0.40, the total energy savings ranged from **1-5%** in a **cold climate** and **8-13%** in a **hot climate.** With lower window areas, the total energy savings ranged from **1-2%** in a **cold climate** and **5-7%** in a **hot climate.** The impact of shade use is proportional to the WWRs in all climates.

The results also show that the savings mainly come from **cooling energy savings** while the heating energy is reduced with the application of white shades. Dark shades only save a very small amount of heating energy while providing losses in cooling energy.

Detailed results on envelope loads and internal heat gains

Two representative cases for hot and cold climates are used to further study the effect of shade properties, especially envelope loads and internal heat gains of buildings. The representative cities are Minneapolis and Phoenix with a long thin E-W building. Window A (SHGC=0.70/ U=2.68/ Tvis=0.79) and WWR 0.40 are used. Figures **4-1** to **4-6** show two graphs each; the top graph shows the monthly envelope loads with glazing, wall, ceiling, floor, partition, ventilation and infiltration loads in kWh/m^2; while the bottom graph shows the monthly building internal heat gains with lighting, computer and equipment, occupancy (latent gain), solar gain from exterior windows, zone/system sensible heating, and zone/system sensible cooling in kWh/m^2. The tabulated detailed energy use (kWh/m^2) is shown in Appendix **A-3** to **A-8**

This analysis addressed the window conduction heat gains and losses, solar gain through windows, and heating and cooling loads as follows:

For Minneapolis [Figures **4-1** to **4-3**], in winter when shades are not applied, window glazings show high glazing heat losses and high solar gains. When white shades are applied, the glazing losses are reduced as well as the solar gain through the windows. The loss of solar gain exceeds any thermal benefits needed. The heating loads increase slightly when compared to the case without shade. Dark shades help reduce glazing losses and absorb solar heat gain which help reduce the heating loads for winter when compared to the case without shades. In summer, however, higher cooling energy is required. White shades helps reduces glazing losses and cut out high solar gains which benefits the cooling systems. Dark shades absorb solar energy which causes the cooling loads to increase. However, over the cause of the year, white shades can provide more energy savings when compared to dark shade and no shade cases.

For Phoenix [Figures **4-4** to **4-6**], since cooling energy is required in both winter and summer. It is showed that white shades provide the highest cooling savings over the cause of the year.

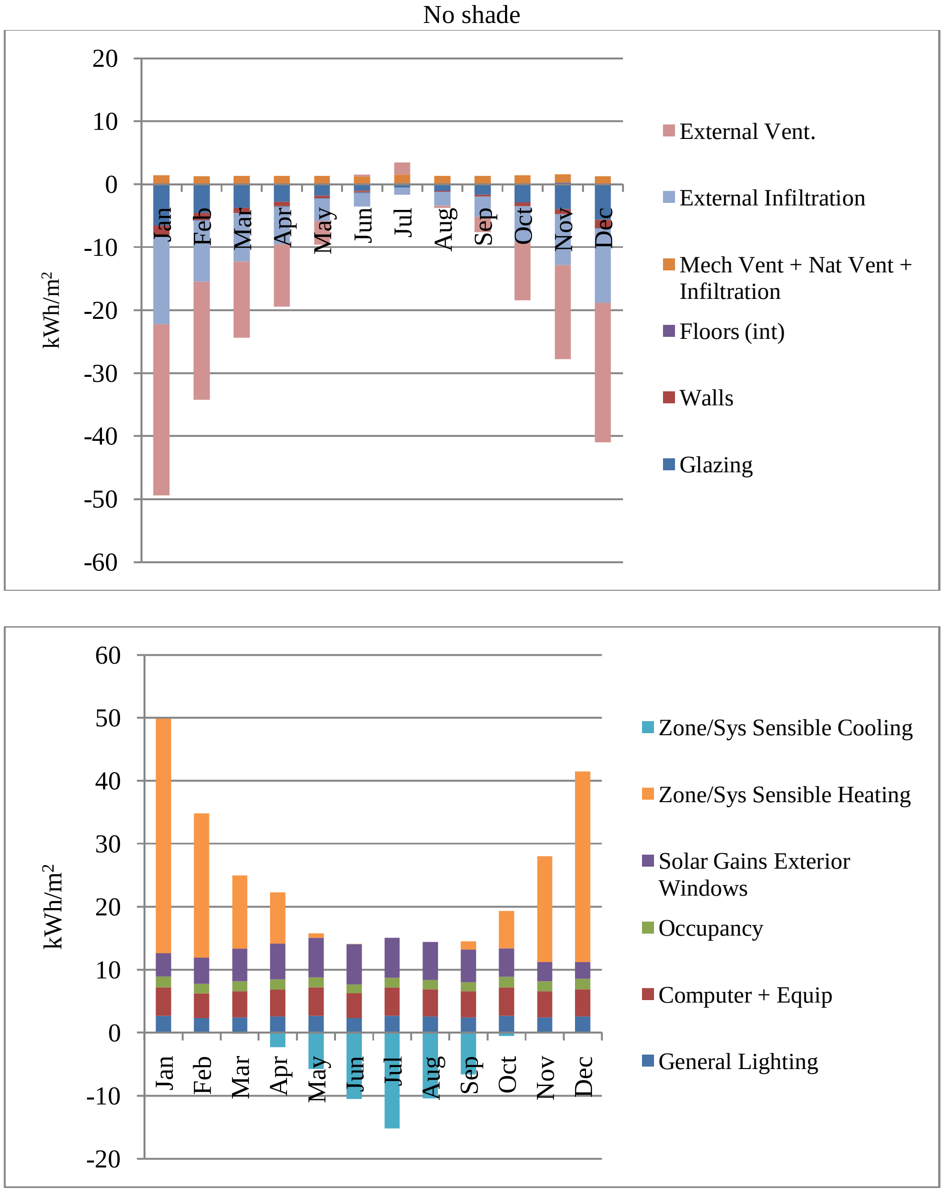


Fig 4-1: Envelope loads and internal gains in Minneapolis, with window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79, WWR of 0.40 without shades (*NS*).

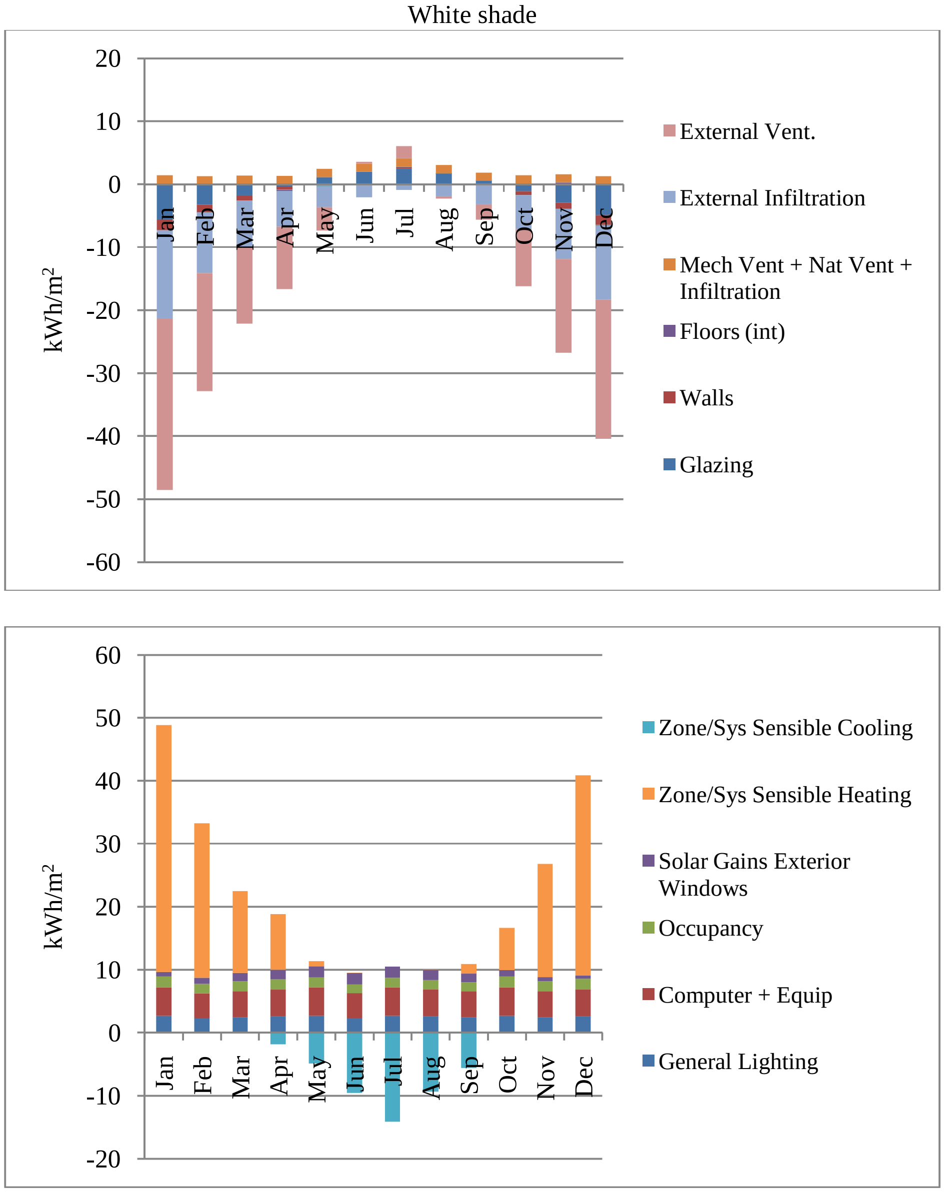
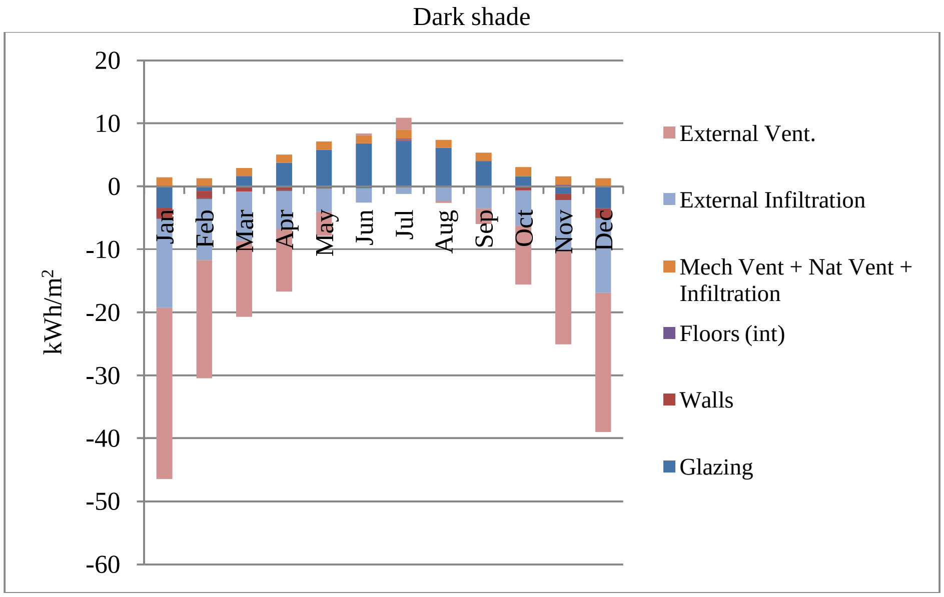


Fig 4-2: Envelope loads and internal gains in Minneapolis, with window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79, WWR of 0.40 with a closed all day white shade (*DN_WS*).



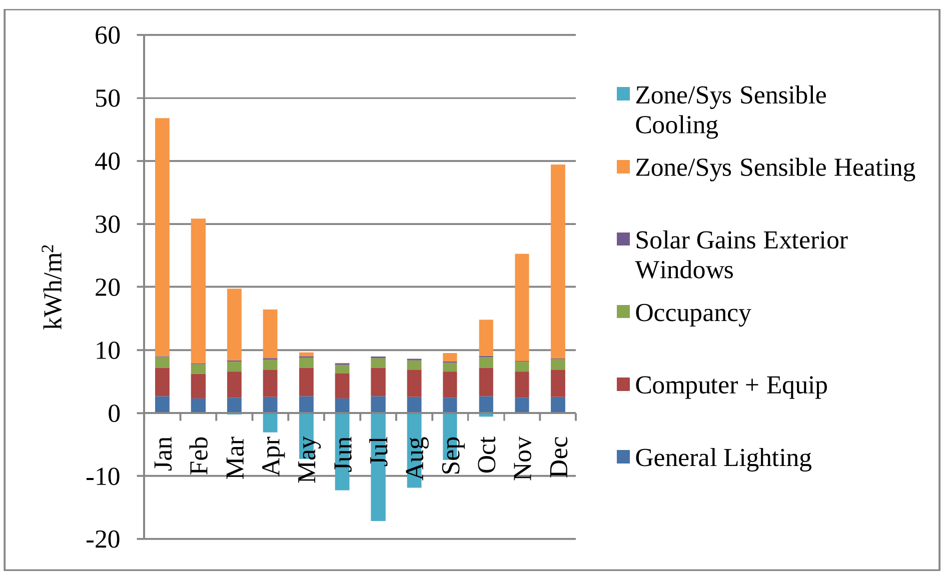


Fig 4-3: Envelope loads and internal gains in Minneapolis, with window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79, WWR of 0.40 with a closed all day dark shade (*DN_DS*).

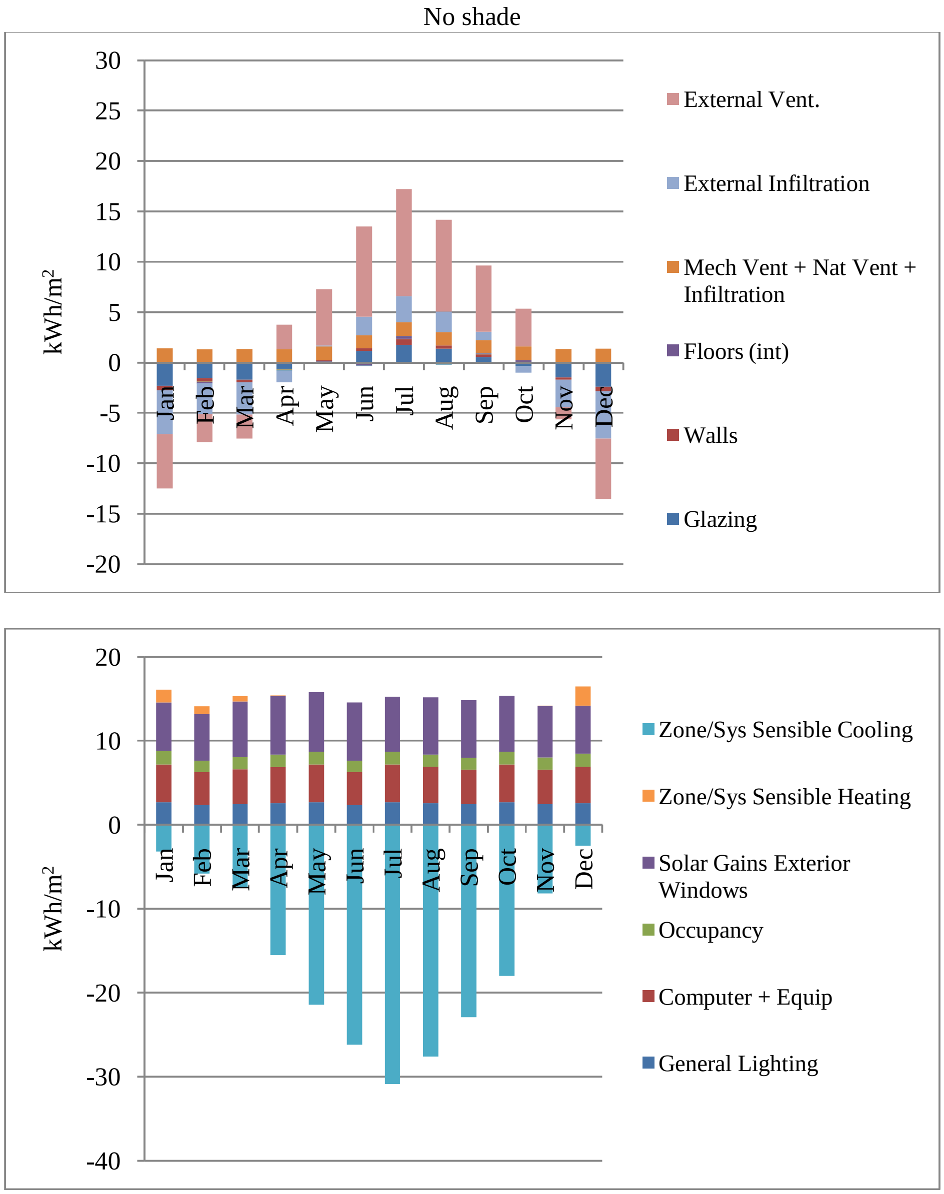


Fig 4-4: Envelope loads and internal gains in Phoenix, with window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79, WWR of 0.40 without shades (*NS*).

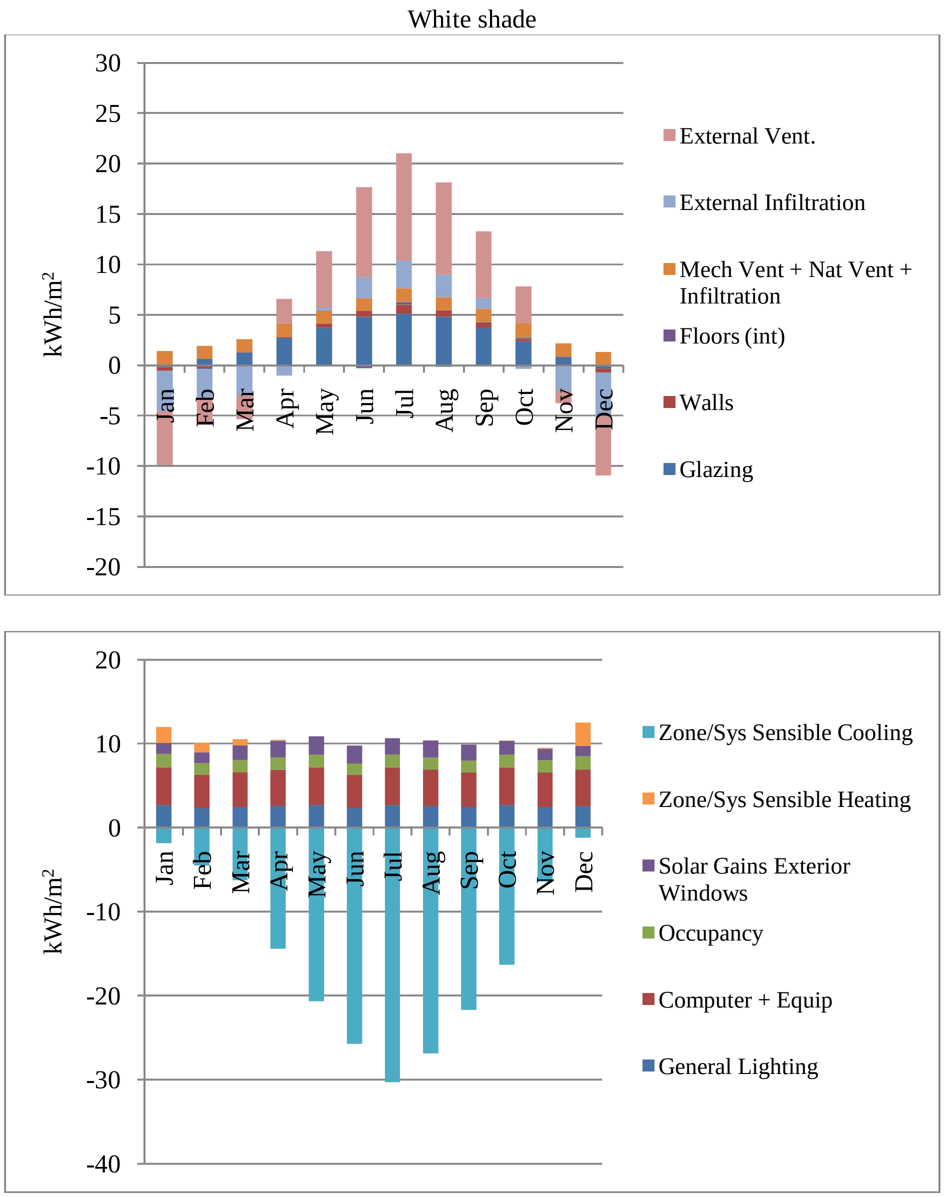


Fig 4-5: Envelope loads and internal gains in Phoenix, with window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79, WWR of 0.40 with a closed all day white shade (*DN_WS*).

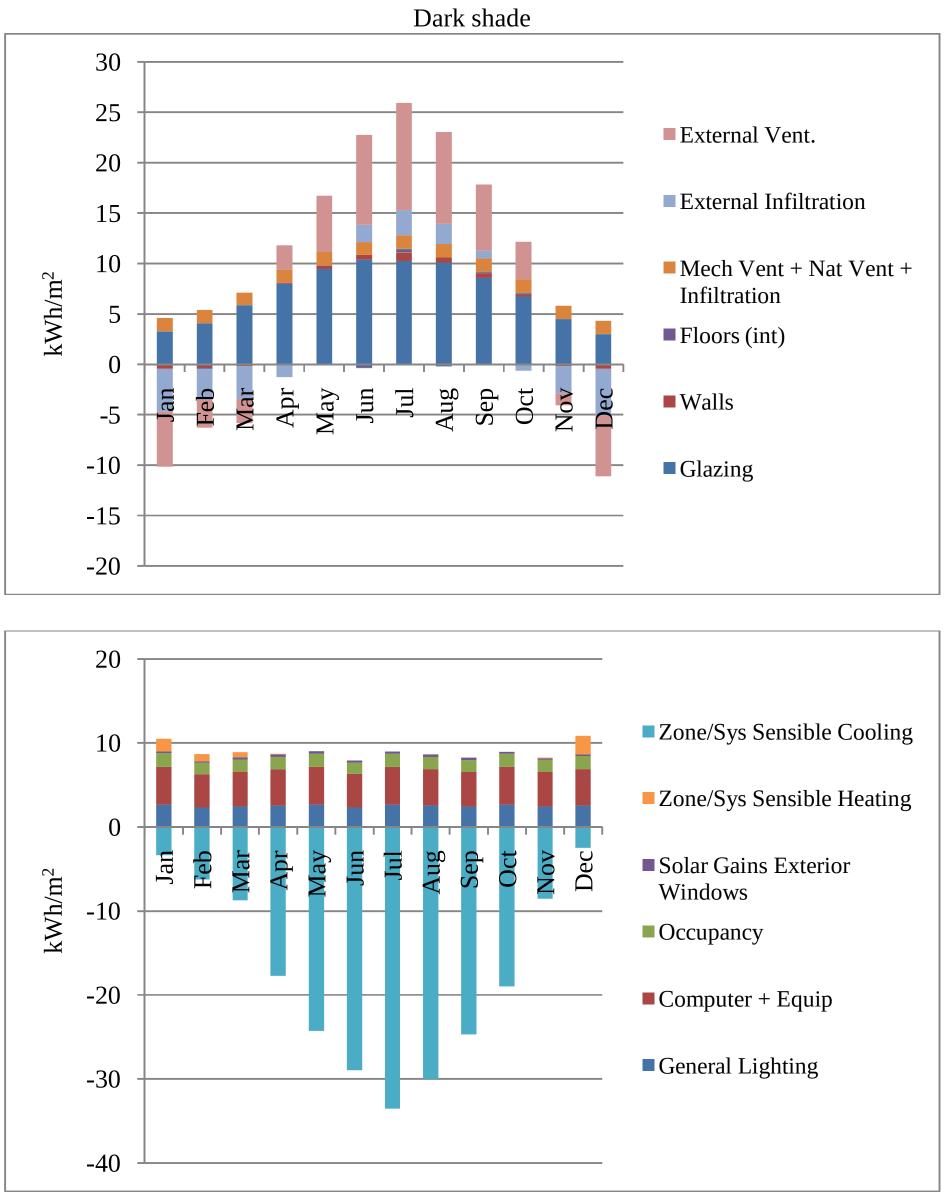


Fig 4-6: Envelope loads and internal gains in Phoenix, with window A, standard double clear glazing, (SHGC=0.70/ U=2.68/ Tvis=0.79), WWR of 0.40 with a closed all day dark shade (*DN_DS*).

Seasonal Optimization

From the previous figures, the use of shades impacts energy use during summer and winter months based on the climate. A test of the seasonal control of shades in the cold and the hot climates with a long thin E-W building, a standard double clear glazing (window A; SHGC=0.70/ U=2.68/ Tvis=0.79) and WWR=0.40 was further analyzed. The goal was to optimize shades used during the winter months. The special control used is a shade closed all day during summer months (*DN_WS_summer* and *DN_DS_summer)*. Shades are closed all day from April to September and opened for the rest of the year. Table **4-3** shows total percent energy savings and energy use for Minneapolis and table **4-4** for Phoenix. Tables **4-3** to **4-4** and figures **4-7** and **4-8** present internal gain comparisons between shades used only in the summer as opposed to all year long.

For Minneapolis, by leaving shades open during winter months, white shades can benefit of cooling energy savings during the summer months [Figure **4-7**]. Hence, total energy savings improve from the shade closed control (*DN_WS*) 2.78% to 5.20%. Dark shades do not show significant total energy savings. Leaving shades up all day may not be a realistic condition during the wintertime but this analysis shows the impact of shades optimized for building envelope loads.

For Phoenix, the total energy savings when shades are used all the time (*DN_WS, DN_DS)* are higher than when shades are in use during the summer time only. This is due to cooling loads during winter months from transmitted solar loads through the windows [Figure **4-8**]. The total energy savings for white and dark shades, when used all day all year, are 16.36% and 7.03%, while the total energy savings for white shades, when used only in the summer, are only 6.73% with dark shades showing an energy increase. The use of shades in the hot climate still provides higher savings than in the cold climate except for the dark shades with summer month control.

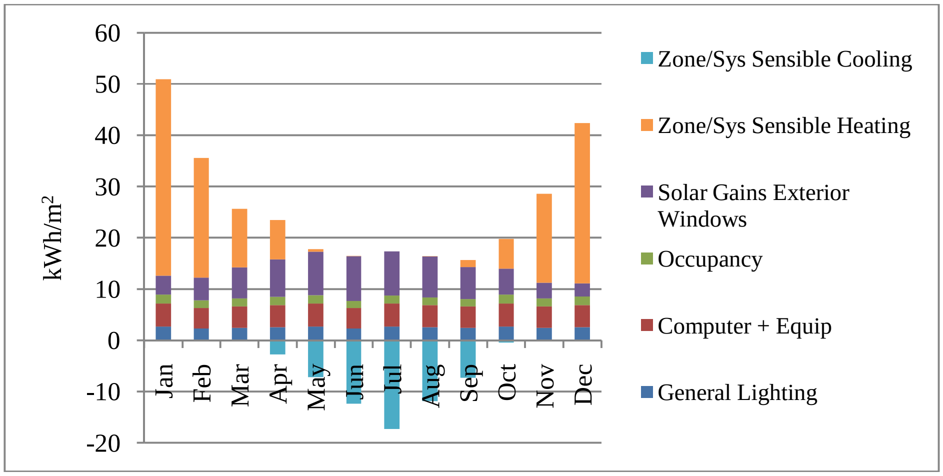
Table 4-3: Total energy savings on a long thin E-W building in a hot climate, AZ, with shades closed all day and no lighting control. A negative percentage represents an increase in the energy required (window A, standard double clear glazing, SHGC=0.70/ U=0.49/ Tvis=0.79, WWR=0.20).

Cities	MN_A_40				AZ_A_40			
Control	*DN_WS*	*DN_DS*	*DN_WS _summer*	*DN_DS _summer*	*DN_WS*	*DN_DS*	*DN_WS _summer*	*DN_DS _summer*
Heating	-3.41%	0.65%	-0.79%	-0.07%	-0.57%	0.24%	-0.39%	-0.39%
Cooling	6.19%	-0.17%	5.99%	-0.03%	133.29%	53.49%	56.10%	-8.14%
Lighting	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	2.78%	0.49%	5.20%	-0.10%	16.36%	7.03%	6.73%	-1.42%

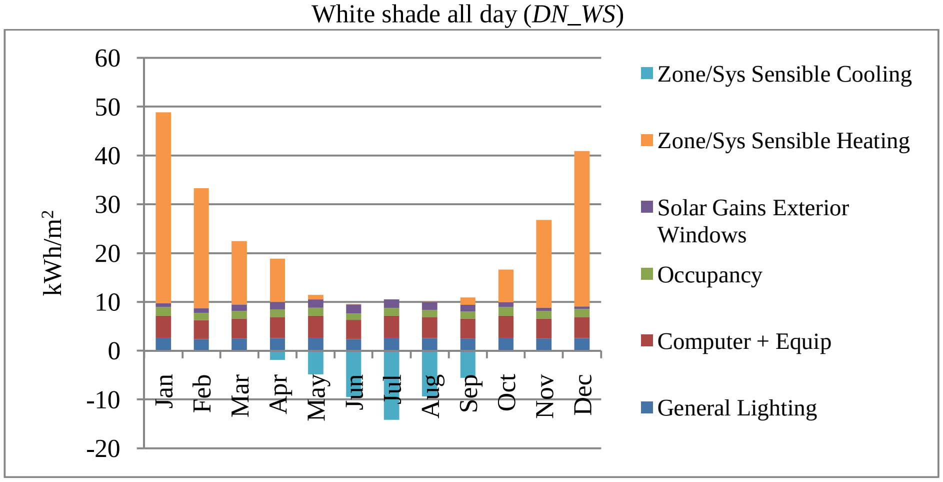
Table 4-4: Total energy use (kWh/m^2) on a long thin E-W building in a hot climate, AZ, with shades closed all day and no lighting control (window A, standard double clear glazing, SHGC=0.70/ U=0.49/ Tvis=0.79, WWR=0.20).

Cities	MN_A_40 (kWh/m^2)					AZ_A_40 (kWh/m^2)				
Control	*NS*	*DN _WS*	*DN _DS*	*DN _WS_ summer*	*DN _DS_ summer*	*NS*	*DN _WS*	*DN _DS*	*DN _WS_ summer*	*DN _DS_ summer*
Heating	136.89	144.62	135.41	138.69	137.05	4.17	5.53	3.6	5.11	5.09
Cooling	59.59	45.55	59.97	46.00	59.66	204.38	163.94	188.15	187.36	206.85
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	226.82	220.52	225.72	215.03	227.05	238.89	199.81	222.09	222.81	242.28

No shade



White shade all day (*DN_WS*)



White shade summer all day *(DN_WS_summer)*

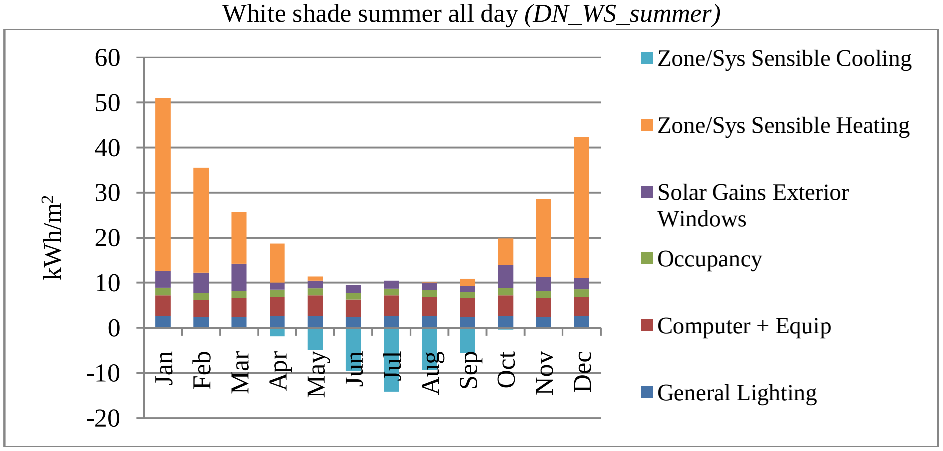


Fig 4-7: Internal gains comparison in Minneapolis with window A, standard double clear glazing, (SHGC=0.70/ U=2.68/ Tvis=0.79), WWR of 0.40 without shades (*NS*), with white shades (*DN_WS*) and with white shades during summer only.

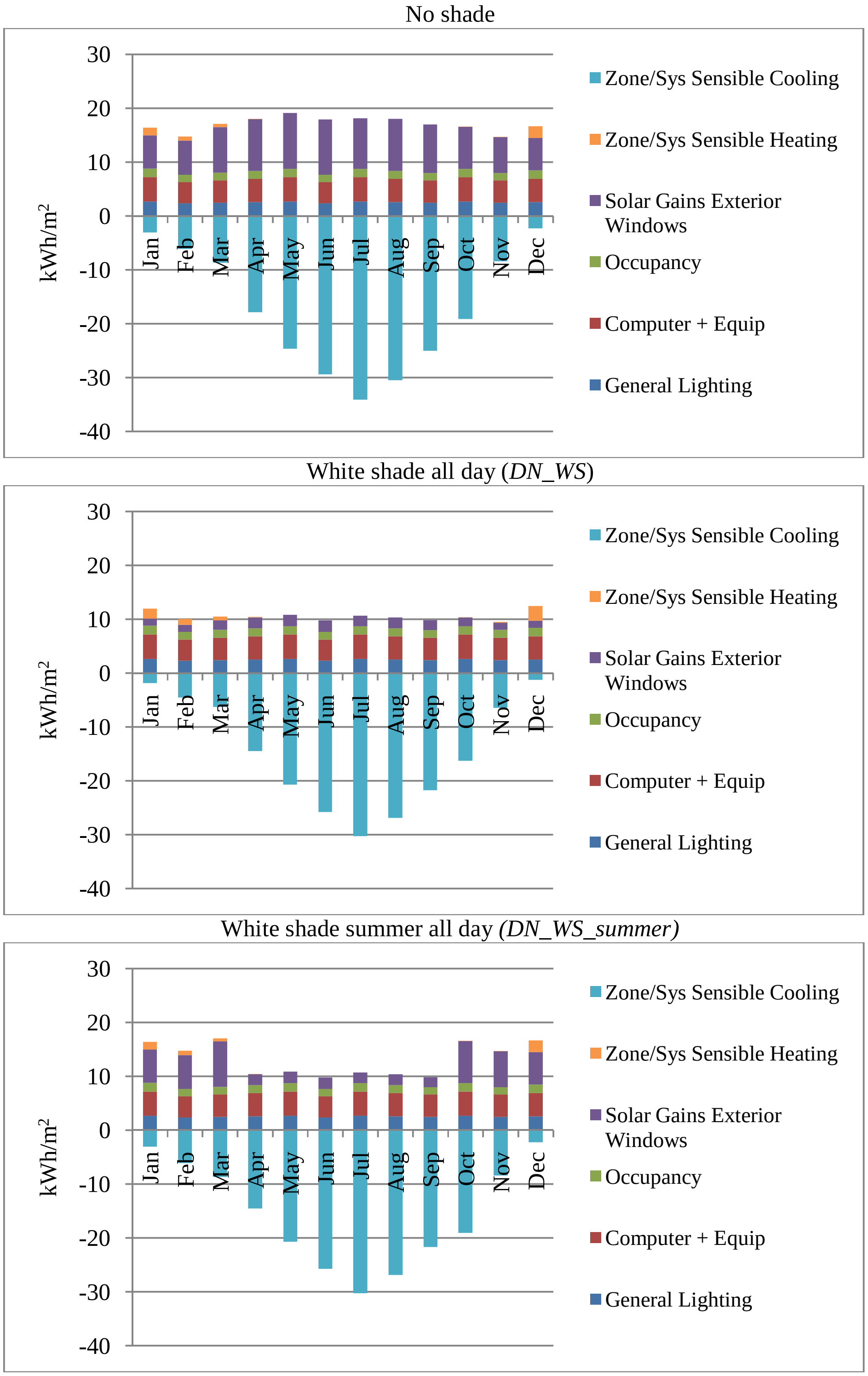


Fig 4-8: Internal gains comparison in Phoenix with window A, standard double clear glazing, (SHGC=0.70/ U=2.68/ Tvis=0.79), WWR of 0.40 without shades (*NS*), with white shades (*DN_WS*) and with white shades during summer only.

4.2.2 Impact of a closed all day shade control with a lighting control system (*DN_ctr*)

The impact of shades on total energy savings is reported in table **4-5**. The difference from the previous set is that lighting controls are applied to all perimeter areas with double-clear windows (window A) and shades to represent existing buildings. The detailed total energy use per building area are reported for a square, a long thin N-S and a long thin E-W building for WWR=0.40. The energy savings are proportional to WWRs in all climates.

The detailed results are reported in appendix **A-9**. Since cases with lighting control systems and no shade do not represent a realistic condition due to the direct sunlight admission, these cases are omitted.

Building geometry and climate

White shades generally perform better than dark shades. The results also show that savings mainly come from lighting and cooling savings with the highest fraction from the cooling savings. The highest cooling savings for white shades in a long thin E-W building range from 8-11% for a cold climate to 14-16% for a hot climate. The highest lighting energy savings of 3-4% occurred with white shades in a long thin E-W building for both climates compared to a square and a long thin N-S building.

The case study buildings are composed of two zones, perimeter and core zones. Lighting control is applied only in the perimeter zone. Hence, the impact of lighting control is not obvious.

A long thin N-S building shows the second highest total energy savings, while a square building presents the lowest total energy savings in all climates.

The highest total energy savings (bold values in tables **4-5**) compared to the base case occurred when white shades are used in a hot climate region. The total energy savings for a cold climate is from 6-11%, with 16-19% achieved in a hot climate.

From the results, there are small differences in total energy savings between geometries while the significant differences are observed for the shade properties, building zones and the use of lighting control systems in different climates. The perimeter zone is studied further in the next section.

Table 4-5: Total energy savings for different building geometries in cold climates, MN, PA and WA, with shades closed all day and lighting control *(DN_ctr)*. A negative percentage represents an increase in energy required (window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40).

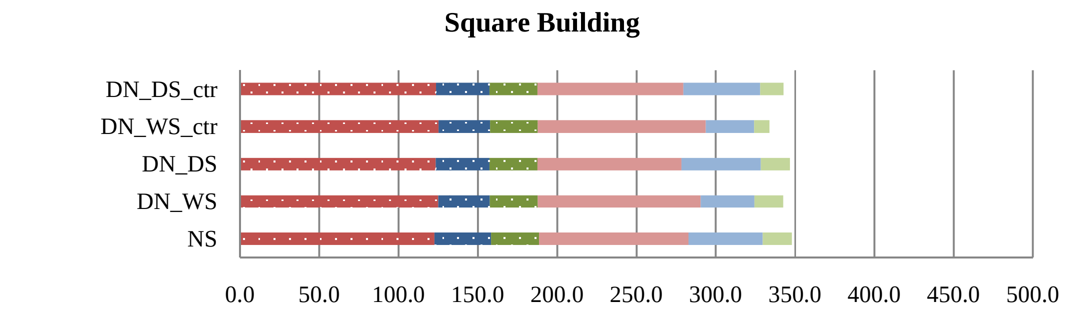
		PA		MN		WA		TX		AZ	
		DN_ WS_ ctr	*DN_ DS_ ctr*	*DN_ WS_ ctr*	*DN_ DS_ ctr*	*DN_ WS_ ctr*	*DN_ DS_ ctr*	*DN_ WS_ ctr*	*DN_ DS_ ctr*	*DN_ WS_ ctr*	*DN_ DS_ ctr*
Square	H	-4.61%	0.01%	-4.22%	0.31%	-5.08%	0.15%	-1.35%	-0.1%	-0.76%	-0.1%
	C	8.80%	0.18%	5.80%	0.13%	7.91%	-0.3%	12.19%	0.74%	13.16%	1.11%
	L	3.40%	1.35%	2.48%	0.99%	3.82%	1.54%	3.38%	1.30%	2.80%	1.14%
	T	7.59%	1.53%	4.06%	1.44%	6.65%	1.38%	14.23%	1.95%	15.20%	2.12%
Long thin N-S	H	-6.01%	-0.3%	-5.69%	0.07%	-6.40%	-0.1%	-2.38%	-0.9%	-0.87%	-0.2%
	C	9.93%	0.50%	6.36%	0.34%	8.76%	0.03%	11.98%	-0.7%	14.46%	1.64%
	L	4.22%	1.69%	3.08%	1.25%	4.70%	1.92%	4.18%	1.62%	3.32%	1.34%
	T	8.13%	1.87%	3.76%	1.66%	7.06%	1.87%	13.78%	-0.1%	16.91%	2.82%
Long thin E-W	H	-5.20%	-0.2%	-4.70%	0.16%	-5.85%	-0.1%	-2.10%	-0.6%	-0.90%	-0.2%
	C	**11.2%**	0.77%	**7.6%**	0.50%	**10.4%**	0.10%	**13.8%**	-0.2%	**16.2%**	1.93%
	L	**4.22%**	1.75%	**3.10%**	1.31%	**4.78%**	2.02%	**4.27%**	1.71%	**3.39%**	1.46%
	T	**10.3%**	2.34%	**6.01%**	1.96%	**9.30%**	2.03%	**16.0%**	0.89%	**18.7%**	3.21%

Perimeter and core zone

Further study on the impact of shades for core and perimeter zone is done in this section. The test is done for Minneapolis with the shades closed all day with and without lighting control (*DN* and *DN_ctr*). Double-pane clear windows (window A SHGC=0.70/ U=2.68/ Tvis=0.79) and two shade colors are used. The detailed total energy savings per zone, energy use per zone and energy per building area (kWh/m^2) are reported for a square, a long thin N-S and a long thin E-W geometry for WWR = 0.40 in table **4-6** and figures **4-9 to 4-11**.

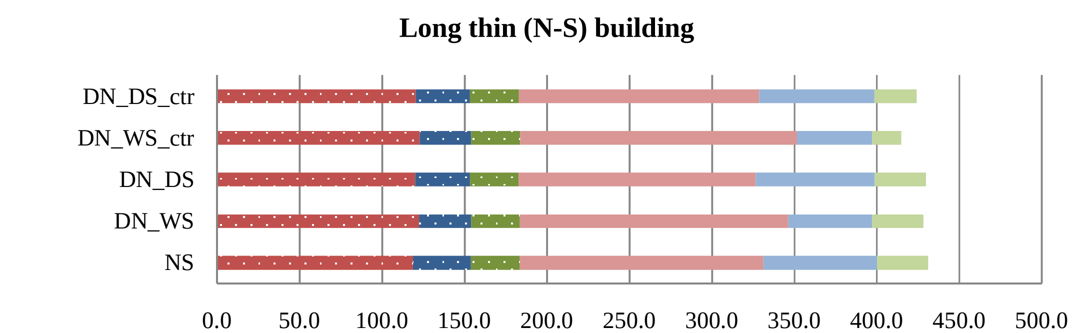
Table 4-6: Total energy savings on different building geometries in cold climates, MN, PA and WA, with shades closed all day control and lighting control *(DN_ctr)*. A negative percentage represents an increase in energy required (window A, standard double clear glazing; SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40).

	Square				Long thin E-W				Long thin N-S			
	DN_ WS	*DN_ DS*	*DN_ WS_ ctr*	*DN_ DS_ ctr*	*DN_ WS*	*DN_ DS*	*DN_ WS_ ctr*	*DN_ DS_ ctr*	*DN_ WS*	*DN_ DS*	*DN_ WS_ ctr*	*DN_ DS_ ctr*
Heating - core	-2%	-1%	-2%	-1%	-2%	-1%	-3%	-1%	-3%	-1%	-3%	-1%
Cooling - core	9%	5%	10%	6%	13%	8%	14%	9%	10%	6%	11%	6%
Lighting - core	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Heating - perimeter	-9%	3%	-13%	2%	-8%	3%	-12%	1%	-10%	3%	-14%	1%
Cooling - perimeter	28%	-7%	36%	-3%	28%	-5%	36%	-1%	26%	-5%	34%	-1%
Lighting - perimeter	0%	0%	47%	19%	0%	0%	45%	19%	0%	0%	43%	17%



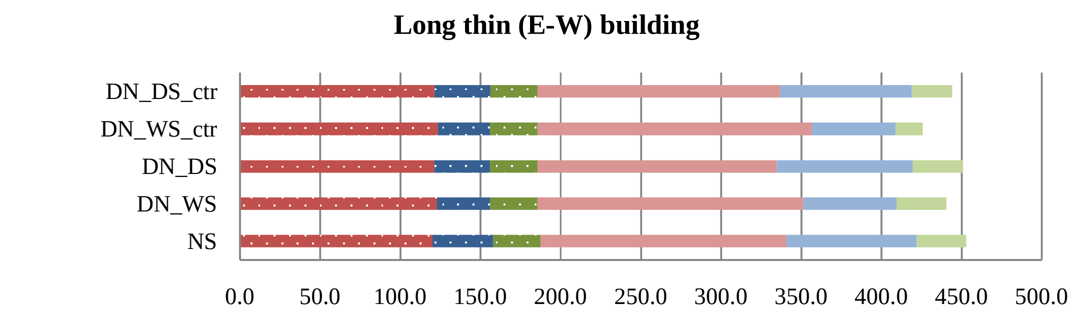
	NS	DN_WS	DN_DS	DN_WS_ctr	DN_DS_ctr
Heating -core	122.6	124.9	123.4	125.3	123.5
Cooling -core	35.8	32.6	33.8	32.3	33.7
Lighting -core	30.3	30.3	30.3	30.3	30.3
Heating -perimeter	93.9	102.6	90.7	105.9	91.9
Cooling -perimeter	46.9	33.8	50.1	30.3	48.5
Lighting -perimeter	18.3	18.3	18.3	9.7	14.9

Fig 4-9: Heating cooling and lighting energy use (kWh/m^2) in a square building in Minneapolis, with shades closed all day with and without lighting control *(DN and DN_ctr)* (window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40).



	NS	DN_WS	DN_DS	DN_WS_ctr	DN_DS_ctr
Heating -core	118.7	122.3	120.2	122.7	120.4
Cooling -core	35.2	31.8	33.1	31.4	33.0
Lighting -core	29.5	29.5	29.5	29.5	29.5
Heating -perimeter	147.6	162.7	143.7	168.0	145.7
Cooling -perimeter	69.0	50.8	72.1	45.4	69.7
Lighting -perimeter	31.0	31.0	31.0	17.8	25.7

Fig 4-10: Heating cooling and lighting energy use (kWh/m^2) in a long thin (N-S) building in Minneapolis, with shade closed all day with and without lighting control *(DN and DN_ctr)* (window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40).



	NS	DN_WS	DN_DS	DN_WS_ctr	DN_DS_ctr
Heating -core	120.1	122.8	121.1	123.4	121.3
Cooling -core	37.9	33.0	34.8	32.5	34.6
Lighting -core	29.5	29.5	29.5	29.5	29.5
Heating -perimeter	153.3	165.9	149.3	171.3	151.3
Cooling -perimeter	81.0	58.0	84.9	51.9	82.1
Lighting -perimeter	31.0	31.0	31.0	17.0	25.1

Fig 4-11: Heating cooling and lighting energy use (kWh/m^2) in a long thin (E-W) building in Minneapolis, with shades closed all day with and without lighting control *(DN and DN_ctr)* (window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40).

The results from figures **4-9** to **4-11** and appendix **A-10** to **A-12** show that;

Perimeter zones contribute more to the change in energy use in a building compared to the core zones. A long thin E-W building shows the highest perimeter loads followed by a long thin N-S building and a square building due to the higher area with more intense solar radiation, hence, the higher total energy savings. The total energy for each energy category (heating, cooling, and lighting) is presented in table **4-7** to **4-9**.

For core zones, white shades show cooling savings of about 10% in all geometries while heating loads is slightly increased about 1-2%. Dark shades show slightly cooling savings of 5% and the same heating load increase of 1-2%.

For perimeter zones, white shades closed all day with lighting control (*DN_WS_ctr*) shows the highest **lighting energy savings** of 42.74%, 45.12% and 46.91% for a long thin (E-W), a long thin (N-S) and a square building respectively. A square building benefits from this shade and lighting control strategy the most. When dark shades all day with lighting control (*DN_DS_ctr*), the heating energy savings increased while the loss of cooling energy balances out the HVAC savings, resulting in savings from lighting control of 17-19% in all three geometries. The second highest energy savings is **cooling energy savings** with 34.19%, 35.56% and 35.89% compared to the base case for a long thin E-W, a square and a long thin N-S building respectively.

The total energy savings are in the range of 3-6% for a shade closed all day with white shades and lighting control (*DN_WS_ctr*) from different geometries.

Table 4-7: Core and perimeter zone total energy savings comparison in a square building, Minneapolis, with shades closed all day with and without lighting control *(DN_ctr)*. A negative percentage represents an increase in energy required (window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.799, WWR=0.40).

Square Building MN_A_40	*DN_WS*	*DN_DS*	*DN_WS_ctr*	*DN_DS_ctr*
Heating -core	-1.89%	-0.66%	-2.18%	-0.79%
Cooling -core	8.86%	5.35%	9.68%	5.64%
Lighting -core	0.00%	0.00%	0.00%	0.00%
Heating -perimeter	-9.24%	3.43%	-12.74%	2.17%
Cooling -perimeter	27.92%	-6.72%	**35.56%**	-3.29%
Lighting -perimeter	0.00%	0.00%	**46.91%**	18.83%
Total – whole building	1.52%	0.34%	**4.06%**	1.44%

Table 4-8: Core and perimeter zones total energy savings comparison in a long thin N-S building, Minneapolis, with shades closed all day with and without lighting control *(DN_ctr).* A negative percentage represents an increase in energy required (window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.799, WWR=0.40).

Long thin (N-S) Building MN_A_40	*DN_WS*	*DN_DS*	*DN_WS_ctr*	*DN_DS_ctr*
Heating -core	-2.30%	-0.84%	-2.73%	-1.02%
Cooling -core	13.09%	8.21%	14.23%	8.65%
Lighting -core	0.00%	0.00%	0.00%	0.00%
Heating -perimeter	-8.27%	2.58%	-11.75%	1.27%
Cooling -perimeter	28.45%	-4.75%	**35.89%**	-1.27%
Lighting -perimeter	0.00%	0.00%	**45.12%**	19.03%
Total – whole building	2.78%	0.49%	**3.76%**	1.66%

Table 4-9: Core and perimeter zones total energy savings comparison in a long thin E-W building, Minneapolis, with shades closed all day with and without lighting control *(DN_ctr),* a negative percentage represents an increase in energy required (window A, standard double clear glazing , SHGC=0.70/ U=2.68/ Tvis=0.799, WWR=0.40).

Long thin (E-W) Building MN_A_40	*DN_WS*	*DN_DS*	*DN_WS_ctr*	*DN_DS_ctr*
Heating -core	-2.97%	-1.20%	-3.38%	-1.38%
Cooling -core	9.80%	5.95%	10.93%	6.34%
Lighting -core	0.00%	0.00%	0.00%	0.00%
Heating -perimeter	-10.23%	2.66%	-13.80%	1.31%
Cooling -perimeter	26.39%	-4.53%	**34.19%**	-1.07%
Lighting -perimeter	0.00%	0.00%	**42.74%**	17.31%
Total – whole building	0.70%	0.34%	**6.01%**	1.96%

4.3 Room level results

The results at the room level for individual perimeter private offices are presented in this section.

For the room level, the study addresses the impact of shades with **high performance windows** as would be typical of **new buildings**. The better performance double pane windows used in this study were non low-E window B (SHGC=0.38/ U=2.73/ Tvis=0.60), low-E window C (SHGC=0.24/ U=1.62/ Tvis=0.60) and low-E window D (SHGC=0.28/ U=1.61/ Tvis=0.64). Window A was simulated without shades for comparison.

Figure **4-12** shows the comparison of energy savings between a base case (*NS*) with window A, standard double clear window, and the higher performance window, window D (Low-E windows) throughout five different cities.

When windows are changed from a standard double pane clear window (Window A) to a better performance window (low-E) such as window D, an energy savings of 8-25% is realized across all orientations without shades. Shades help provide additional savings on top of the savings received from the better window. The additional shade savings are about 1-10% when shades are used all day (*DN*) compared to the base case with window A.

For some cases, by changing windows alone in a specific city and orientation; total energy loss occurred, such as in Seattle on the north, south and east façades.

The automatic shade control strategies consist of the shade closed all day without lighting control (*DN*) and two automatic control strategies with lighting control (*EMWA_ctr, Solxxx_ctr*).

The results of these analyses are separately presented for heating-dominated and cooling-dominated cities for WWR=0.40. Heating-dominated cities are Minneapolis (MN), Philadelphia (PA) and Seattle (WA). Cooling-dominated cities are Houston (TX) and Phoenix (AZ). Within these results, orientation (North, South, East and West), glazing type suitable for that particular region (Window A, B, C, and D), shade colors (WS and DS) and the use of lighting control systems (with lighting control: _ctr; and without lighting control) are addressed.

The performance of the different shade control strategies are described in detail. Annual total, heating, cooling and lighting energy use and savings are compared for each case. The base case throughout this section is a room without shades and no lighting control (*NS*) for each glazing type. All parameters in this section were simulated using EnergyPlus.

Figure **4-13** compares the results for a heating-dominated and cooling-dominated city, Minneapolis and Phoenix, for their heating (H), cooling (C) and lighting (L) loads in a test space on each orientation. The proportion of H, C, and L for a test space in Minneapolis is about 70%, 15%, 15%, while the energy proportions for Phoenix are 10%, 60%, 30%. These proportions differ slightly across building orientations.

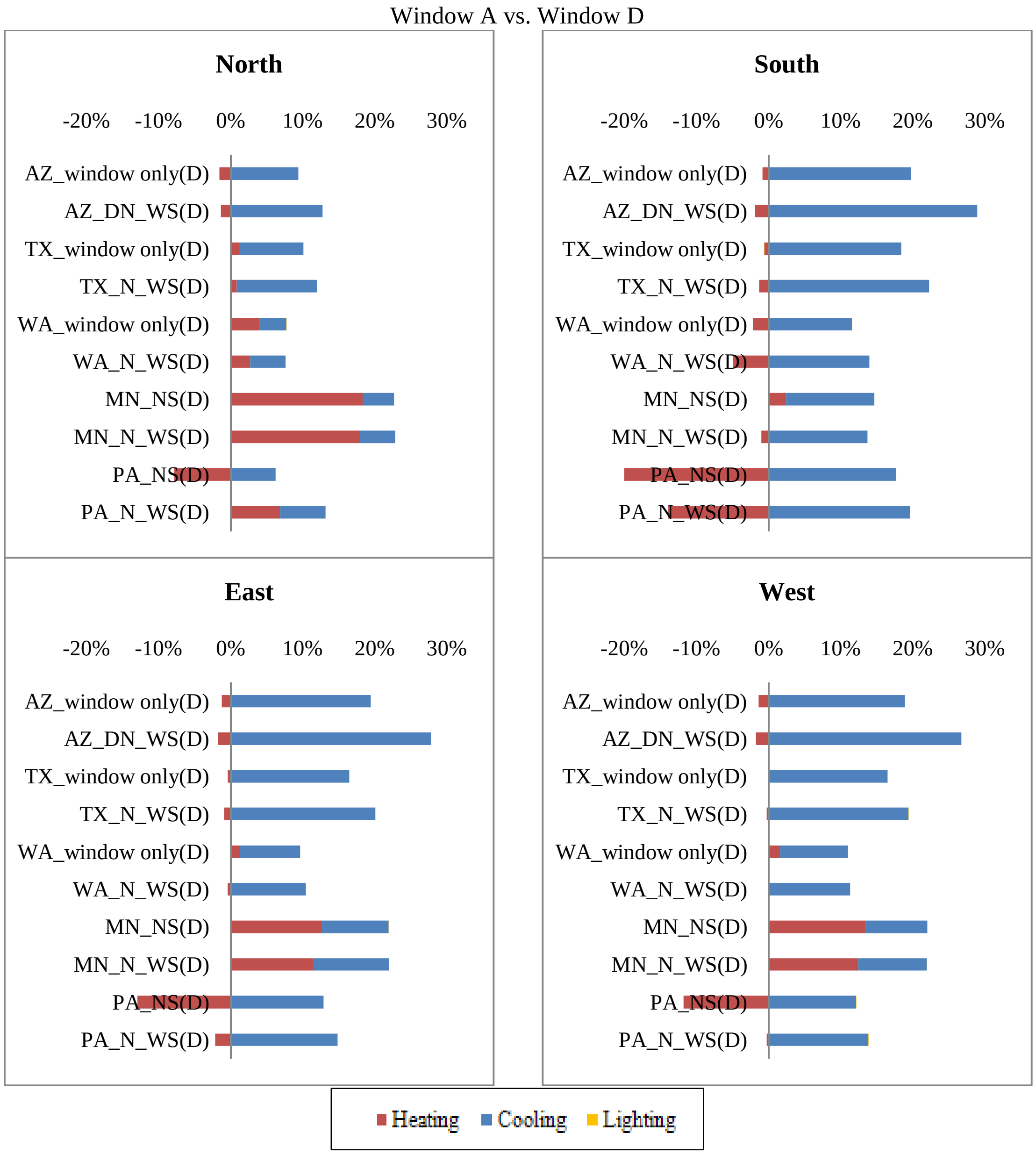


Fig 4-12: Heating, cooling and lighting energy savings between a base case (*NS*) with window A, standard double clear window, and the better performance window, window D (Low-E windows) throughout five different cities.

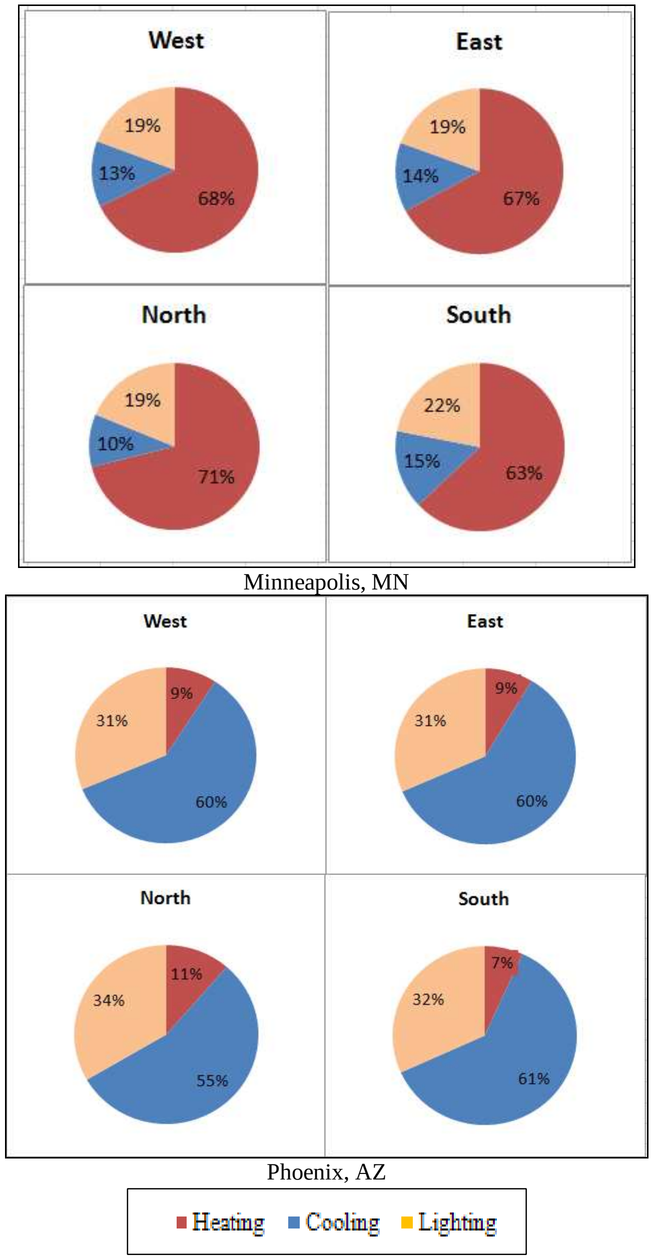


Fig 4-13: Heating, cooling and lighting energy use proportions in Minneapolis and Phoenix across all orientations.

4.3.1 Impact of shades on total, heating, cooling and lighting energy use and savings with a shade closed all day (*DN, DN_ctr*) and an automatic shade control strategy (*EMWA_ctr*) with and without lighting control systems

4.3.1.1 Heating –dominated region

Space heating energy represents the largest fraction of building energy consumption in colder climates like Minneapolis (MN), Philadelphia, (PA), and Seattle (WA). The proportion of space heating (H), cooling (C), and lighting (L) energy (H%,C%,L%) for PA, MN and WA averaged across all orientations are PA (50%,25%,25%), MN (70%,15%,15%) and WA (40,%25%,35%).

First, to determine the impact of shade use on total energy savings, the cases with a shade closed all day with and without lighting control, *DN* and *DN_ctr,* and one automatic control strategy, a time control strategy with lighting control *(EMWA_ctr),* were tested. The use of lighting control is denoted with a*_ctr* following the control strategy name. The cases are applied with a standard double pane clear window, window A (SHGC=0.70/ U=2.68/ Tvis=0.79) as might be present in an existing buildings. In addition, two insulated double pane low-E windows, window B (SHGC=0.38/ U=2.73/ Tvis=0.60) and window D (SHGC=0.28/ U=1.61/ Tvis=0.64), are used with a WWR of 0.20 and 0.40. These low–E windows comply with the ASHRAE glazing recommendations for this region. Both white shades (*WS*) and dark shades (*DS*) were applied.

The different shade control strategies are:

- A base case, with no shade OR lighting control, denoted *NS.*
- A shade closed all day (*DN, DN_ctr*), applied with and without a lighting control. These cases are labeled: *DN_WS*, *DN_ DS*, *DN_ WS_ctr* and *DN_DS_ctr*.
- A time schedule control with lighting control (*EMWA_ctr*) is applied with shades activated on the east façade in the morning (7am-1pm DST), the west façade in the afternoon (1pm-7pm DST), no shading on the north, and all-day shading on the south façade. The lighting control systems are also activated. These cases are labeled *EMWA_WS_ctr* and *EMWA_DS_ctr*. The reason for applying time schedule control is to maximize the lighting energy savings during the time that sunlight does not shine directly onto a window. The results are reported as the impact of shades on total energy savings and heating, cooling and lighting energy use for the different test cases. Total annual space energy use for the base case in PA averaged across all orientations ranges from 84-135 kWh/m^2 (8-13 kWh/ft^2), MN ranges from 133-213 kWh/m^2 (12-20 kWh/ft^2), and WA ranges from 68-112 kWh/m^2 (6.3-10.4 kWh/ft^2).

Tables **4-10** to **4-12** report total energy savings between each control strategy and the base case that considers no shading or lighting control (*NS*) for WWR 0.20 and 0.40 with three different glazings, A, B and D. Figures **4-14** to **4-16** offer more insight into the factors that drive the differences in heating and cooling energy use for each orientation and control strategy. The case shown for the detailed heating, cooling and lighting energy use is for window D (SHGC=0.28/ U=1.61/ Tvis=0.64).

Impact on total energy savings

Tables **4-10 to 4-12** and figures **4-14 to 4-16** show the annual energy savings across different control strategies and test parameters. The results are as follows.

White shades show higher total energy savings than dark shades in most cases. Dark shades, however, still provide some savings. This is due to higher solar loads that create heating energy savings when used with the better SHGC glazings such as window B (SHGC=0.38/ U=2.73/ Tvis=0.60) and window D (SHGC=0.28/ U=1.61/ Tvis=0.64). The savings from dark shades also occur when coupled with a time control strategy for most glazings and WWRs. However, in some cases, dark shade savings can result in a loss of energy on a south orientation when applied with a time control strategy. This is due to the time control strategy closing the shades all day on this facade.

For control strategies, the shade closed all day shade control strategy without lighting control (*DN*) does not provide significant savings for both shade colors, all three cold-climate suitable glazings and the two WWRs, and may result in higher total energy use. When lighting control systems are in use (*DN_ctr*), the savings are more significant and can be up to 10.64% with WWR=0.40 for window A and a white shade in Seattle.

A time control strategy with lighting control (*EMWA_ctr*) displays the best overall performance when compared to the other strategies and provides the maximum total energy savings across cities, glazings and shade colors. The savings are different across the orientations as shown on figure 4-10 to 4-12. The savings from a time control strategy range from 1-22%, 1-18% and 1-21% for window A, C and D across all orientations.

In Philadelphia, all three windows (window A, B and D) show similar total energy savings for both shade colors with WWR 0.20 and 0.40. The savings are slightly higher for WWR=0.40 and white shades.

In Minneapolis, better glazings (window B and D) reduce the impact of shades towards total energy savings. And with a time control strategy, higher savings can be achieved, with the greatest savings obtained with a white shade when used with window A and a WWR of 0.20.

In Seattle, the two WWRs show different levels of savings. WWR=0.40 shows the best overall savings, while WWR=0.20 shows the best performance on a north orientation only. Window D with a time control strategy shows the highest savings with a white shade and WWR of 0.40.

The results show that different orientations provide different energy savings, with the highest savings occurring on the north facade, followed by the east and west. The least savings occur on the south façade. Further analysis is performed in the next section.

The differences between WWR suggest that WWR=0.40 can provide about 2 times as muck savings in most of the cases except in Minneapolis when the glazing is a double pane clear window (window A). The savings are higher from WWR=0.20 than 0.40 in Minneapolis.

Optimizing control strategies

Further study on how to optimize total energy savings across orientations, shade colors, and control strategies are presented in figures **4-17** to **4-19** and **A-13** to **A-15**. Three test cases were analyzed in the three cooler climate cities, Philadelphia, Minneapolis and Seattle, with window D and WWR=0.40. They show that,

A time control strategy with lighting control (*EMWA_WS_ctr*) provides energy savings mainly through lighting control (7-24% of the total energy). Cooling energy savings also contribute to the overall total energy savings but to a lesser degree (1-5%) depends on orientation). There are generally losses on heating energy, but overall, this control condition still provides more total energy savings than the all-day control strategy.

Regarding orientation, all three cities show different control strategies and shade colors that can be used to optimize total energy savings as follows.

North and East façades can apply a time control strategy for both white and black shades (*EMWA_WS _ctr* and *EMWA_DS_ctr*).

The south façade can apply closed white shades with lighting control.

The west façade can apply a time control strategy with white shades.

If only one control strategy is to applied to all orientations of a building, a time control strategy with white shades should be used, which provides the maximum annual total energy savings in all three cities.

Table 4-10: Total energy savings in the cold climates, MN, PA and WA, with a shade closed all day with and without lighting control system (*DN*, *DN_ctr*) and a time control strategy *(EMWA_ctr)* with window A (SHGC=0.70/ U=2.68/ Tvis=0.79).

Philadelphia with window A WWR=0.20 (PA_A_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.30%	3.73%	**10.41%**	-0.27%	-0.30%	6.54%
East	0.14%	5.68%	**11.24%**	0.66%	1.56%	8.21%
North	0.29%	2.61%	15.64%	0.72%	0.70%	**15.69%**
South	-0.48%	2.98%	**3.78%**	0.39%	1.54%	1.73%

Philadelphia with window A WWR=0.40 (PA_A_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.62%	7.13%	**13.87%**	-1.83%	-0.11%	6.60%
East	1.10%	9.84%	**15.53%**	-0.32%	2.57%	11.04%
North	-0.18%	4.67%	16.18%	0.26%	1.47%	**16.26%**
South	0.72%	9.96%	**11.03%**	-2.42%	0.39%	0.76%

Minneapolis with window A WWR=0.20 (MN_A_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.29%	3.61%	**11.42%**	0.42%	0.26%	8.82%
East	-0.53%	4.42%	**10.23%**	0.33%	0.91%	6.38%
North	-0.47%	2.31%	**22.30%**	-0.37%	-0.82%	22.10%
South	0.56%	2.13%	**4.81%**	-0.21%	-0.14%	3.02%

Minneapolis with window A WWR=0.40 (MN_A_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.05%	3.91%	**7.17%**	0.05%	1.08%	3.75%
East	0.48%	5.75%	**8.48%**	0.83%	2.60%	6.65%
North	0.20%	2.85%	8.94%	1.44%	2.10%	**8.96%**
South	-4.78%	0.96%	**1.56%**	-0.64%	1.15%	1.31%

Seattle with window A WWR=0.20 (WA_A_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.29%	3.61%	**11.42%**	0.42%	0.26%	8.82%
East	-0.53%	4.42%	**10.23%**	0.33%	0.91%	6.38%
North	-0.47%	2.31%	**22.30%**	-0.37%	-0.82%	22.10%
South	0.56%	2.13%	**4.81%**	-0.21%	-0.14%	3.02%

Seattle with window A WWR=0.40 (WA_A_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	2.03%	8.66%	**15.43%**	-1.58%	0.19%	6.69%
East	1.77%	10.29%	**16.95%**	0.31%	2.91%	12.16%
North	-0.46%	4.54%	18.40%	0.62%	1.92%	**18.49%**
South	2.19%	10.64%	**11.61%**	-1.21%	1.13%	1.37%

Light grey highlighted shows the maximum savings from white shades

Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

A – Window (A standard double clear glazing ,SHGC=0.70/ U=2.68/ Tvis=0.79)

20,40 - Window-to-wall ratio 0.20 to 0.40

Table 4-11: Total energy savings in the cold climates, MN, PA and WA, with a shade closed all day with and without lighting control (*DN*, *DN_ctr*) and a time control strategy *(EMWA_ctr)* with window B (SHGC=0.38/ U=2.73/ Tvis=0.60).

Philadelphia with window B, WWR=0.20 (PA_B_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.14%	3.48%	**10.27%**	0.66%	1.01%	8.86%
East	0.29%	5.66%	**10.05%**	0.72%	1.46%	6.01%
North	-2.83%	0.44%	17.83%	0.39%	0.93%	**21.33%**
South	1.08%	-2.79%	1.62%	**3.24%**	-6.72%	-0.52%

Philadelphia with window B, WWR=0.40 (PA_B_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.55%	5.20%	**10.31%**	0.50%	1.67%	6.57%
East	0.83%	7.65%	**12.93%**	1.30%	3.23%	10.04%
North	1.04%	4.42%	14.73%	1.59%	2.42%	**14.78%**
South	-1.43%	4.87%	**5.79%**	0.32%	2.07%	2.25%

Minneapolis with window B, WWR=0.20 (MN_B_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	-0.16%	1.31%	**3.04%**	0.29%	0.64%	2.13%
East	-0.04%	2.50%	**5.67%**	0.62%	1.25%	4.65%
North	0.23%	1.30%	7.56%	0.68%	0.93%	**7.58%**
South	-1.77%	-0.03%	0.22%	0.49%	0.93%	**0.96%**

Minneapolis with window B, WWR=0.40 (MN_B_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.31%	3.10%	**5.52%**	0.96%	1.65%	3.68%
East	0.56%	4.71%	**7.41%**	1.45%	2.62%	6.02%
North	0.84%	2.70%	8.24%	1.60%	2.05%	**8.27%**
South	-2.49%	1.19%	1.67%	1.12%	2.11%	**2.15%**

Seattle with window B, WWR=0.20 (WA_B_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.03%	2.09%	**8.12%**	0.52%	0.27%	6.69%
East	-0.22%	3.07%	**7.79%**	0.32%	0.42%	4.88%
North	-0.70%	0.87%	18.24%	0.06%	-0.22%	**19.27%**
South	0.14%	1.27%	**3.83%**	-0.11%	-0.01%	2.78%

Seattle with window B, WWR=0.40 (WA_B_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.01%	4.97%	**10.72%**	-0.41%	0.83%	6.22%
East	0.43%	7.03%	**13.89%**	0.80%	2.60%	10.86%
North	-0.12%	3.36%	16.54%	0.80%	1.67%	**16.61%**
South	-0.51%	5.44%	**6.27%**	-0.11%	1.45%	1.56%

Light grey highlighted shows the maximum savings from white shades

Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

B – Window (A standard double tint glazing ,SHGC=0.38/ U=2.73/ Tvis=0.60)

20,40 - Window-to-wall ratio 0.20 to 0.40

Table 4-12: Total energy savings in the cold climates, MN, PA and WA, with a shade closed all day with and without lighting control (*DN*, *DN_ctr*) and a time control strategy *(EMWA_ctr)* with window D (SHGC=0.28/ U=1.61/ Tvis=0.64).

Philadelphia with window D, WWR=0.20 (PA_D_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.06%	3.37%	**9.43%**	0.13%	0.87%	7.13%
East	0.04%	5.00%	**10.71%**	0.65%	2.04%	8.27%
North	0.25%	2.67%	15.91%	0.56%	1.05%	**15.94%**
South	-1.17%	3.39%	**3.96%**	0.96%	3.02%	3.15%

Philadelphia with window D, WWR=0.40 (PA_D_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	-0.81%	5.76%	**12.23%**	-0.05%	1.34%	7.71%
East	-0.68%	8.15%	**14.56%**	0.80%	3.06%	11.29%
North	-0.60%	4.57%	16.72%	0.93%	1.95%	**16.77%**
South	-2.56%	5.29%	**6.31%**	0.64%	2.56%	2.80%

Minneapolis with window D, WWR=0.20 (MN_D_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	-0.15%	1.51%	**3.66%**	0.23%	0.63%	2.54%
East	-0.08%	2.78%	**6.45%**	0.53%	1.23%	5.17%
North	0.12%	1.34%	8.41%	0.56%	0.84%	**8.43%**
South	-1.37%	0.52%	0.81%	0.59%	1.07%	**1.12%**

Minneapolis with window D, WWR=0.40 (MN_D_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	-0.10%	4.53%	**8.29%**	0.45%	1.43%	5.59%
East	0.05%	6.50%	**10.38%**	0.93%	2.58%	8.15%
North	0.25%	3.66%	**11.82%**	1.03%	1.70%	**11.85%**
South	-2.28%	3.53%	**3.65%**	1.04%	2.39%	2.55%

Seattle with window D, WWR=0.20 (WA_D_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.07%	3.21%	**10.03%**	0.62%	1.21%	8.45%
East	-0.11%	4.47%	**9.41%**	0.44%	1.38%	6.12%
North	-0.43%	2.14%	21.05%	0.30%	0.88%	**22.17%**
South	0.15%	1.47%	**4.12%**	-0.11%	0.10%	2.99%

Seattle with window D, WWR=0.40 (WA_D_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	0.21%	6.74%	**13.00%**	-0.50%	0.99%	7.63%
East	0.41%	8.64%	**15.88%**	0.69%	2.83%	12.45%
North	-0.11%	4.68%	18.76%	0.75%	1.81%	**18.83%**
South	-0.29%	7.18%	**7.62%**	0.02%	1.86%	2.04%

Light grey highlighted shows the maximum savings from white shades

Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)

20,40 - Window-to-wall ratio 0.20 to 0.40

Fig 4-14: Annual total energy savings between different control strategies, shade colors, glazing types and WWRs in Philadelphia.

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)

B – Window (A standard double tint glazing ,SHGC=0.38/ U=2.73/ Tvis=0.60)

D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)
20,40 - Window-to-wall ratio 0.20 to 0.40

Fig 4-15: Annual total energy savings between different control strategies, shade colors, glazing types and WWRs in Minneapolis.

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)

B – Window (A standard double tint glazing ,SHGC=0.38/ U=2.73/ Tvis=0.60)

D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)

20,40 - Window-to-wall ratio 0.20 to 0.40

Fig 4-16: Annual total energy savings between different control strategies, shade colors, glazing types and WWRs in Seattle.

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)

B – Window (A standard double tint glazing ,SHGC=0.38/ U=2.73/ Tvis=0.60)

D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)

20,40 - Window-to-wall ratio 0.20 to 0.40

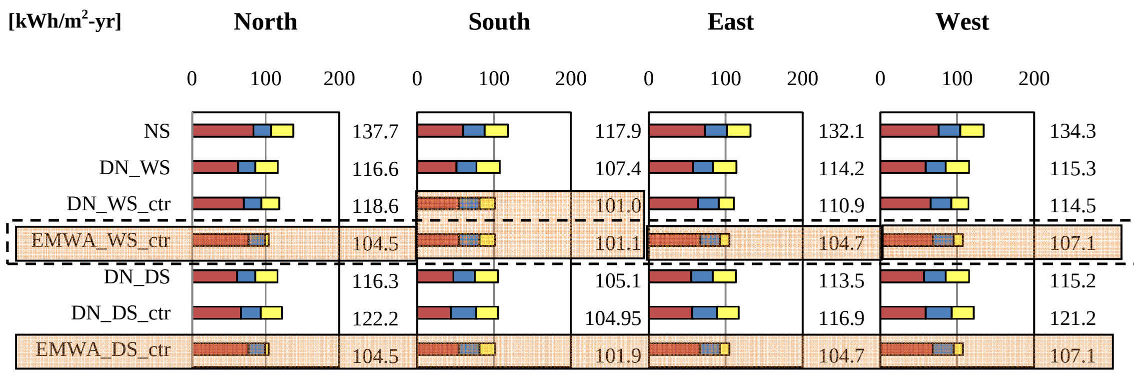


Fig 4-17: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Philadelphia, Window D (SHGC=0.28/ U=1.61/ Tvis=0.64), two shade colors and WWR of 0.40.

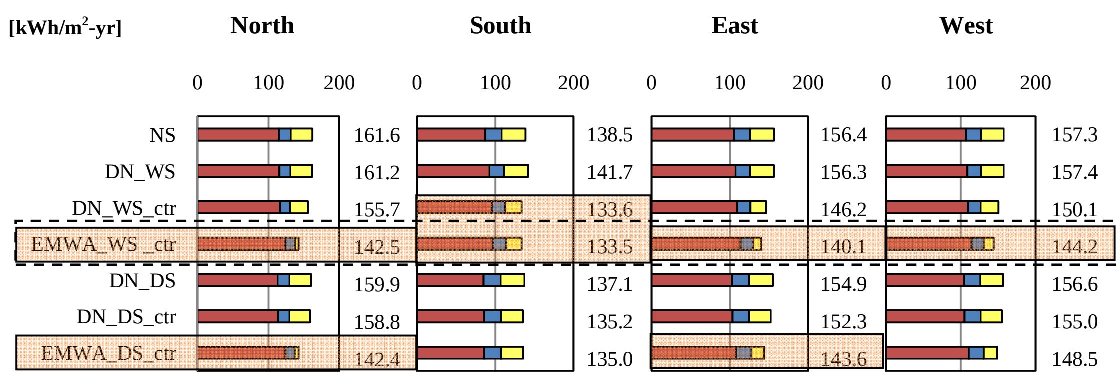


Fig 4-18: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Minneapolis, Window D (SHGC=0.28/ U=1.61/ Tvis=0.64), two shade colors and WWR of 0.40.

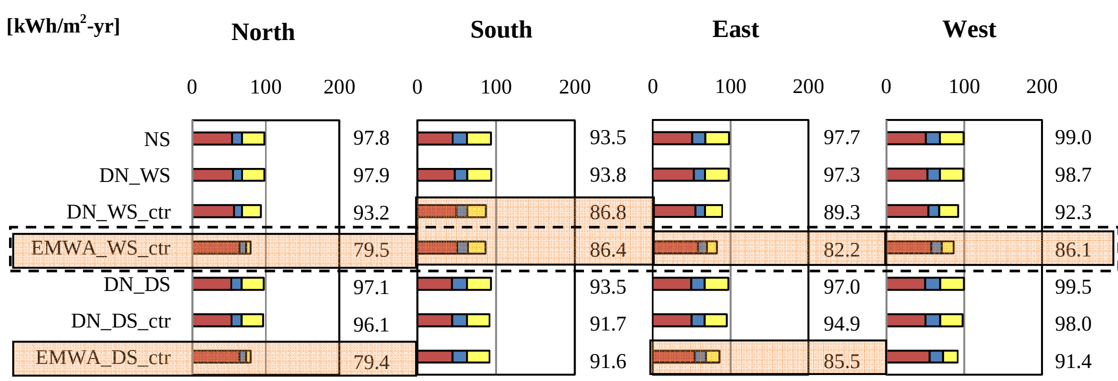


Fig 4-19: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Seattle, Window D (SHGC=0.28/ U=1.61/ Tvis=0.64), two shade colors and WWR of 0.40.

Heating Cooling Lighting

Highlighted area represents the strategies with low total energy use

The dotted line represents the recommended strategy that yields the maximum savings

4.3.1.2 Cooling –dominated region

This section addresses the impact of shades in the hot climate cities, Houston (TX) and Phoenix (AZ). The proportion of space heating (H), cooling (C), and lighting (L) energy (H%, C%, L %) for TX and AZ is averaged across all orientations and is distributed as follows: TX (10%, 60%, 30%), and AZ (5%, 70%, 25%).

First, to determine the impact of shade use on total energy savings, shade closed all day, *DN* and one automatic control strategy, a time control strategy with lighting control *(EMWA_ctr)*, were tested. The cases are applied with a standard double pane clear window, window A (SHGC=0.70/ U=2.68/ Tvis=0.79) as used in existing buildings. In addition, two insulated double pane low-E windows, window C (SHGC=0.24/ U=1.62/ Tvis=0.60) and window D (SHGC=0.28/ U=1.61/ Tvis=0.64), are used with a WWR of 0.20 and 0.40. These low–E windows comply with the ASHRAE glazing recommendation for these cities. Both white shades (*WS*) and dark shades (*DS*) were applied.

Total annual space energy use for the base case in TX averaged across all orientations ranges from 69-123 kWh/m^2 (6-11 kWh/ft^2), and AZ ranges from 59-123 kWh/m^2 (5.5-11.4 kWh/ft^2).

Impact on total energy savings

Results from tables **4-13** to **4-15** and figures **4-20** to **4-21** show that:

White shades show more energy savings over dark shades in this region for all control strategies, glazing types and WWRs while dark shades only save energy when coupled with a time control strategy (*EMWA_ctr*).

For control strategies, shades closed all day (*DN*), shade closed all day with lighting control (*DN_ctr*) and time control with lighting control (*EMWA_ctr*) with white shades all worked well in this region for both WWRs. The highest total energy savings occurs on a time control strategy with white shades with savings that vary across orientations and glazing types. The shades closed all day without lighting control (*DN*) can result in 11.24% total energy savings on the south side with white shades, window A and WWR 0.40 in Houston. Shades closed all day with lighting control (*DN_ctr*) increase the total energy savings about 2 – 2.5 times compared to shades closed all day control without lighting control (*DN*).

A time control strategy with lighting control and white shades shows maximum savings in all cases with ranges of 13-35%, 7-35% and 8-35% for window A, C and D across all orientations.

In both Houston and Phoenix, better glazing (window C and D) reduces the energy savings of shades when applied all day with or without lighting control. With an automatic shade control strategy, the total energy savings are not much different.

The difference between WWRs show a similar trend to the cold climate region, with about 2 times higher total energy savings achieved with the larger size windows when white shades are closed all day with or without lighting control. The differences are not significant when used with a time control strategy with lighting control. Dark shades that are closed all day with and without lighting control do not work well in Houston. However, when applied with a time control strategy, dark shades provide generous savings except on the south façade.

In Phoenix, although white shades perform better than dark shades in general, using dark shades still can result in total energy savings. The higher total energy savings occur in these particular cases: shades closed all day with lighting control (*DN_ctr*) -WWR0.40-window C and D; a time control (*EMWA_ctr*) -WWR 0.40 – window C and D, except on the south orientation. The results also suggest that different orientations are affected by shades differently. If standard glazing (window A) is used in this region, especially on the south façade, shades should be used, with white shades providing better energy performance than dark shades.

Optimizing control strategies

This section addresses the total energy savings optimization across the building orientations as presented in figures **4-22** to **4-23** and **A-16** to **A-17.** Three cases are selected in two cities with window D and WWR=0.40. Again, heating savings do not benefit much from the dark shades in this region since heating energy use is very small. The total energy savings mainly result from lighting energy savings (10-28% of the total energy). Cooling energy savings (6-10%) also contribute to the overall total energy savings to a lesser degree.

The results show that a time control strategy with lighting control *(EMWA_ctr*) can be used on all orientations and provide maximum benefit. Darker shades with a time control strategy can also be used on the north, east and west façade and still provide some savings. The south-facing windows can also be used with a shade closed all day with lighting control and white shades. If only one control strategy is to be applied to all orientations of a building, a time control strategy with white shades should yield the maximum annual total energy savings.

Table 4-13: Total energy savings in hot climates, TX and AZ, with shades closed all day with and without lighting control (*DN*, *DN_ctr*) and a time control strategy *(EMWA_ctr)* with window A (SHGC=0.70/ U=2.68/ Tvis=0.79).

Houston with window A, WWR=0.20, (TX_A_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	4.97%	11.04%	**19.47%**	-1.59%	-0.10%	10.07%
East	5.48%	15.55%	**26.87%**	-0.28%	2.23%	16.49%
North	3.15%	8.72%	32.18%	4.53%	5.90%	**38.38%**
South	5.72%	12.63%	**13.75%**	-0.94%	0.79%	1.05%

Houston with window A, WWR= 0.40, (TX_A_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	9.04%	19.42%	**28.42%**	-2.27%	-0.33%	12.21%
East	9.92%	24.58%	**33.01%**	-1.17%	3.15%	17.50%
North	5.32%	15.25%	**32.45%**	-0.36%	2.07%	**32.44%**
South	11.24%	23.05%	**24.53%**	-1.65%	1.38%	1.88%

Phoenix with window A, WWR= 0.20, (AZ_A_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	6.24%	11.76%	**20.86%**	-1.96%	-4.11%	7.19%
East	7.25%	16.95%	**25.42%**	-0.69%	-1.92%	10.05%
North	3.17%	7.88%	**28.16%**	0.02%	-0.25%	**28.14%**
South	7.99%	14.26%	**15.83%**	-1.28%	-4.11%	-3.75%

Phoenix with window A, WWR= 0.40, (AZ_A_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	3.12%	11.09%	**28.25%**	-2.33%	-20.71%	15.92%
East	3.73%	15.77%	**31.84%**	-1.16%	-18.84%	19.23%
North	2.09%	7.77%	**34.64%**	-0.71%	-11.80%	**34.64%**
South	3.84%	15.15%	**16.86%**	-1.78%	-22.88%	1.54%

Light grey highlighted shows the maximum savings from white shades
Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix
A – Window (A standard double clear glazing , (SHGC=0.70/ U=2.68/ Tvis=0.79)
20,40 - Window-to-wall ratio 0.20 to 0.40

Table 4-14: Total energy savings in hot climates, TX and AZ, with shades closed all day with and without lighting control (*DN*, *DN_ctr*) and a time control strategy *(EMWA_ctr)* with window C (SHGC=0.24/ U=1.62/ Tvis=0.60).

Houston with window C, WWR=0.20, (TX_C_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	1.11%	7.36%	**17.00%**	-0.78%	0.71%	11.24%
East	1.48%	11.82%	**24.70%**	-0.15%	2.33%	17.11%
North	1.01%	6.53%	**32.84%**	-5.58%	-4.12%	**29.11%**
South	1.28%	6.37%	**7.22%**	-11.96%	-10.65%	-10.46%

Houston with window C, WWR=0.40, (TX_C_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	1.78%	10.53%	**21.33%**	-1.95%	-0.11%	12.16%
East	2.40%	15.80%	**28.04%**	-0.94%	2.03%	17.57%
North	1.32%	8.89%	**33.48%**	-0.63%	0.97%	**33.48%**
South	2.32%	12.23%	**13.92%**	-1.46%	0.66%	1.00%

Phoenix with window C, WWR=0.20, (AZ_C_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	1.12%	6.04%	**13.25%**	-1.27%	-1.72%	6.45%
East	1.65%	10.16%	**18.23%**	-0.53%	-0.27%	9.09%
North	0.75%	4.45%	**22.33%**	-0.30%	-0.11%	**22.32%**
South	1.57%	7.17%	**8.38%**	-0.96%	-1.59%	-1.35%

Phoenix with window C 0.40, WWR=0.40, (AZ_C_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	8.97%	15.72%	**25.09%**	5.73%	7.38%	12.13%
East	9.68%	19.86%	**27.81%**	6.60%	9.09%	14.35%
North	3.77%	8.42%	**30.56%**	2.25%	3.39%	**30.54%**
South	9.63%	16.87%	**16.66%**	6.33%	8.12%	-1.31%

Light grey highlighted shows the maximum savings from white shades

Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

C – Window (A standard Low E spectral reflective double glazing , (SHGC=0.24/ U=1.62/ Tvis=0.60)

20,40 - Window-to-wall ratio 0.20 to 0.40

Table 4-15: Total energy savings in hot climates, TX and AZ, with shades closed all day with and without lighting control (*DN*, *DN_ctr*) and a time control strategy (*EMWA_ctr)* with window D (SHGC=0.28/ U=1.61/ Tvis=0.64).

Houston with window D, WWR=0.20, (TX_D_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	1.78%	7.03%	**15.14%**	-1.00%	0.30%	9.42%
East	2.12%	10.77%	**22.95%**	-0.26%	1.90%	15.94%
North	1.38%	6.03%	**30.95%**	-0.02%	1.13%	**30.95%**
South	1.98%	7.86%	**8.83%**	-0.61%	0.87%	1.10%

Houston with window D, WWR=0.40, (TX_D_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	3.12%	11.09%	**28.25%**	-2.33%	-0.35%	15.92%
East	3.73%	15.77%	**31.84%**	-1.16%	1.92%	19.23%
North	2.09%	7.77%	**34.64%**	-0.71%	0.71%	**34.64%**
South	3.84%	15.15%	**16.86%**	-1.78%	1.07%	1.54%

Phoenix with window D, WWR=0.20, (AZ_D_20)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	6.24%	11.76%	**20.86%**	-1.96%	-4.11%	7.19%
East	7.25%	16.95%	**25.42%**	-0.69%	-1.92%	10.05%
North	3.17%	7.88%	**28.16%**	0.02%	-0.25%	**28.14%**
South	7.99%	14.26%	**15.83%**	-1.28%	-4.11%	-3.75%

Phoenix with window D, WWR=0.40, (AZ_D_40)

	DN_WS	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
West	8.81%	15.48%	**24.52%**	5.55%	7.18%	11.47%
East	9.42%	19.52%	**27.72%**	6.41%	8.90%	14.32%
North	3.77%	8.35%	**30.12%**	2.31%	3.43%	**30.11%**
South	9.82%	17.41%	**17.08%**	6.31%	8.19%	-1.94%

Light grey highlighted shows the maximum savings from white shades

Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)

20,40 - Window-to-wall ratio 0.20 to 0.40

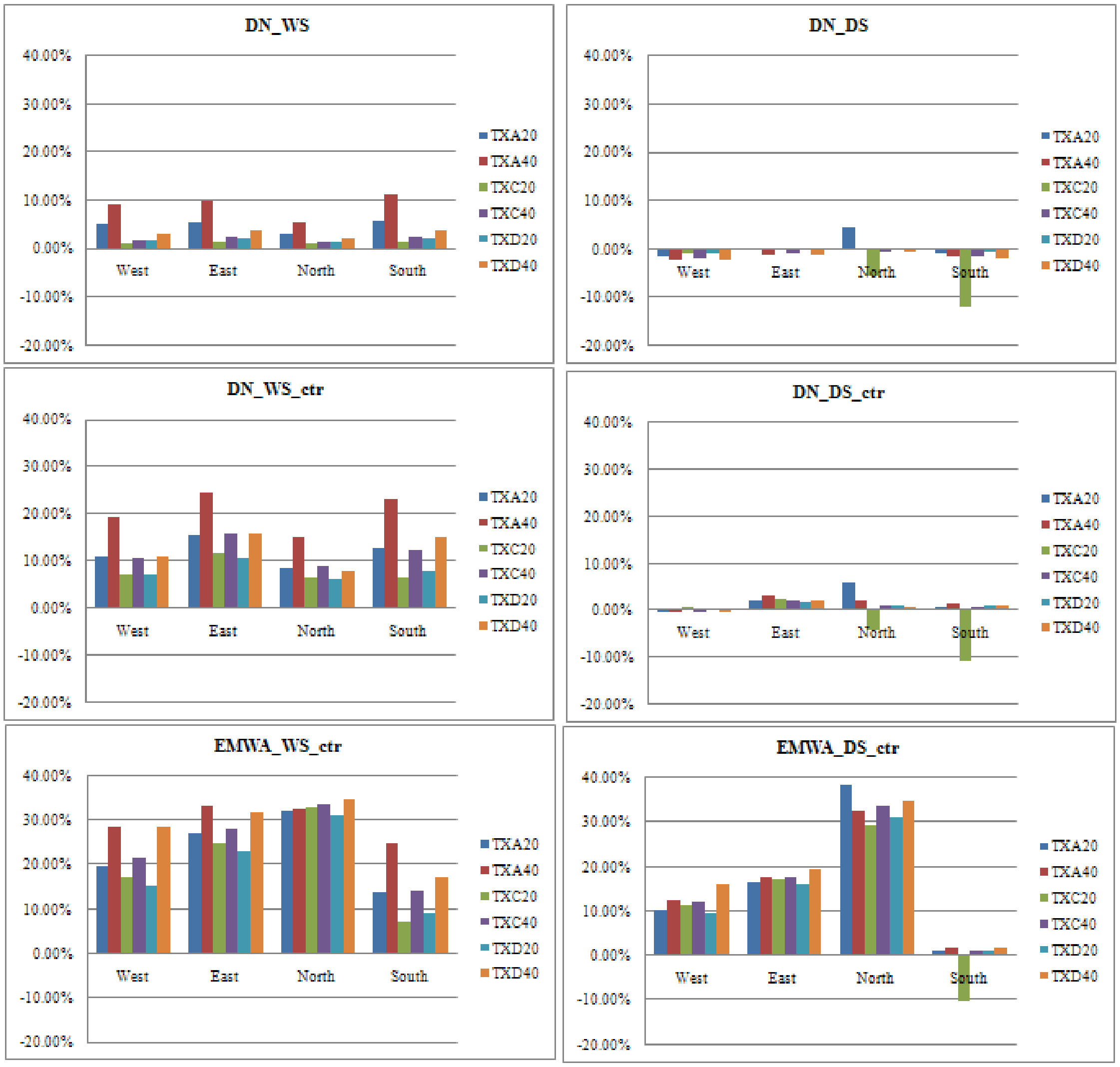


Fig 4-20: Annual total energy savings between different control strategies, shade colors, glazing types and WWRs in Houston.

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)

C – Window (A standard Low E spectral reflective double glazing , (SHGC=0.24/ U=1.62/ Tvis=0.60)

D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)

20,40 - Window-to-wall ratio 0.20 to 0.40

Fig 4-21: Annual total energy savings between different control strategies, shade colors, glazing types and WWRs in Phoenix.

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)

C – Window (A standard Low E spectral reflective double glazing , (SHGC=0.24/ U=1.62/ Tvis=0.60)
D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)
20,40 - Window-to-wall ratio 0.20 to 0.40

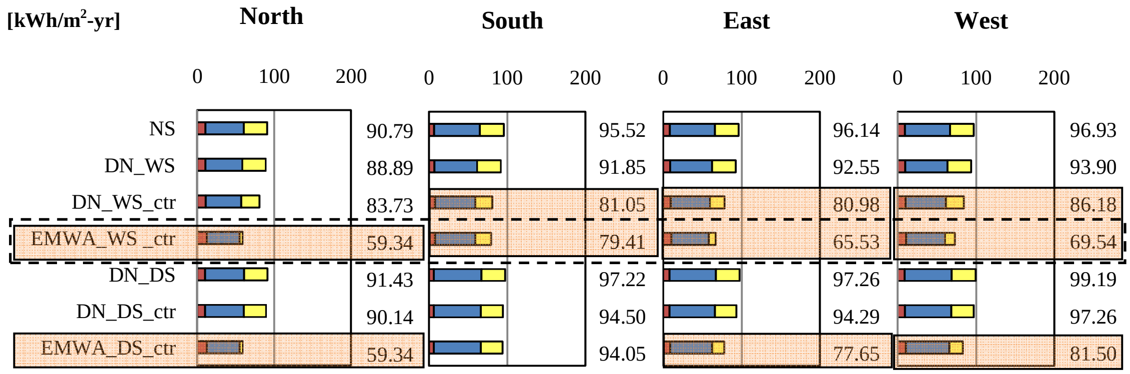


Fig 4-22: Annual total energy (heating, cooling and lighting energy) across different orientations and control strategies: Houston, Window D (SHGC=0.28/ U=1.61/ Tvis=0.64), two shade colors and WWR of 0.40.

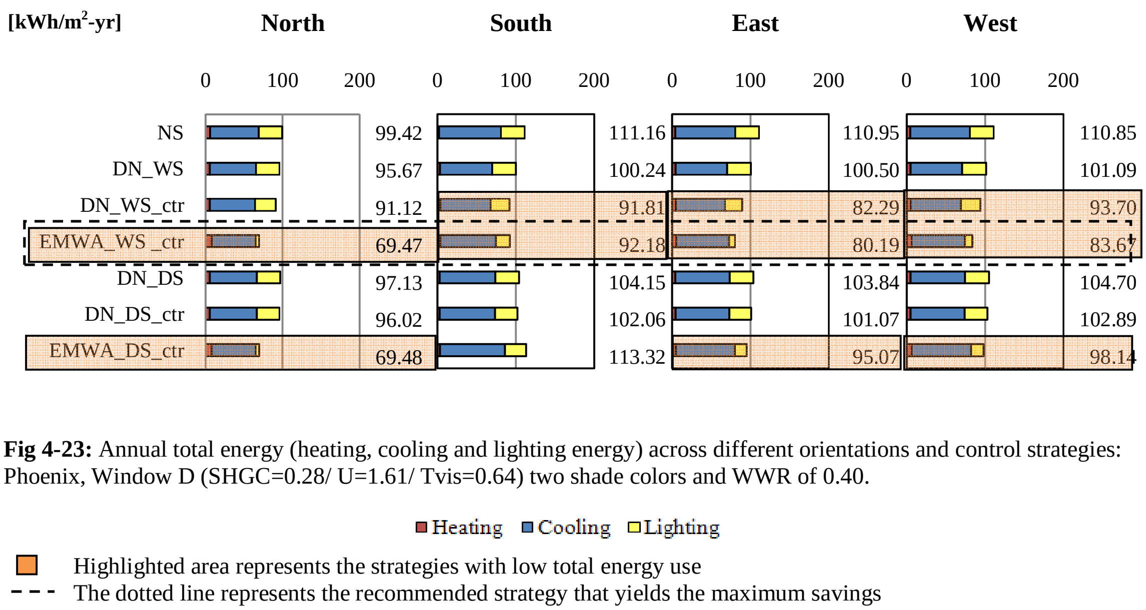


Fig 4-23: Annual total energy (heating, cooling and lighting energy) across different orientations and control strategies: Phoenix, Window D (SHGC=0.28/ U=1.61/ Tvis=0.64) two shade colors and WWR of 0.40.

4.3.2 Impact of shades on total, heating, cooling and lighting energy use and savings with automatic shade control strategies (*Solxxx_ctr*) with a lighting control system

Solar radiation control strategies (*Solxxx_ctr*) denoted *Sol189_ctr*, *Sol378_ctr* and *Sol630_ctr*, are investigated in this section. In these simulations, shades were closed when solar radiation incident on the windows reached the following limits: a low solar control value at 189 W/m^2 (60 Btu/hr-ft^2), a medium solar control value at 378 W/m^2 (120 Btu/hr-ft^2) and a high solar control value at 630 W/m^2 (200 Btu/hr-ft^2). Figure **4-24** shows the difference in the number of hours that shades were applied due to the solar radiation set point. According to the TMY2 weather condition for this particular day, July 15th in Minneapolis, the number of hours the shades dropped are 9, 6 and 5 hours for the low, medium and high solar control strategies respectively.

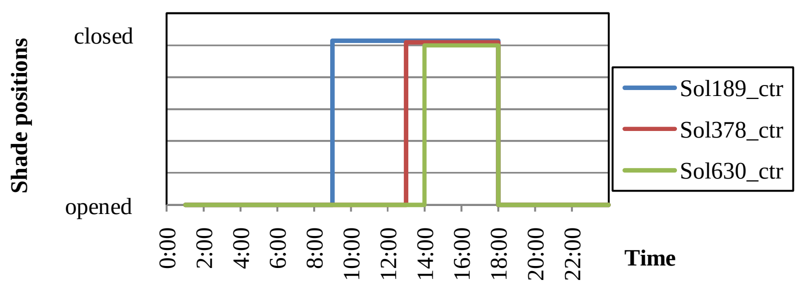


Fig 4-24: Fraction of time a shading device is closed when used with solar radiation control strategies on a west facade on July 15th, clear sky condition, Minneapolis.

All cases use lighting control systems, denoted by *_ctr*. The cases are applied with insulated double pane Low-E windows, Window D, with WWR=0.40. Both white shade (*WS*) and dark shades (*DS*) are applied.

4.3.2.1 Heating-dominated climate

Impact on total energy savings

From table **4-16**, white shades again show better performance than dark shades. Although, further analysis should be made since dark shades can perform better for some orientations and control strategies.

All solar control strategies provide good performance with similar total energy savings throughout the cases. With high solar radiation control, white shades (*WS_Sol630_ctr*) provide the highest total energy savings of 29.4% on the east façade in Philadelphia. The total energy savings are in the range of 19-30% for Philadelphia, 6-14% for Minneapolis, and 12-27% for Seattle.

From table **4-16** and appendix **A-18,** on a north-facing window, all solar control strategies provide similar total energy savings. This is because a low solar control strategy keeps the shades open most of the time. On the east and west façades, the differences are about 1-2% between control set points. The total energy savings differed by 2-10% on south orientations. This is because of different cooling energy savings since lighting energy savings are similar. For dark shades, lighting energy savings have more impact than cooling energy savings when compared to white shades. White shades show high cooling and lighting savings in the range of 14-26% and 60-84% respectively when compared to cooling and lighting loads of the base case. Dark shades did not perform as well in this region, although they still benefit cooling and lighting energy savings in the range of 5-21% and 38-82% respectively when compared to the base case.

Impact on heating, cooling and lighting energy

The lighting energy savings are greater than the savings received from cooling as seen on table **4-16** and appendix **A-18.** These tables show results for Minneapolis with window D and WWR=0.40.

For heating energy, when these solar control strategies are applied with both shade types, heating energy increases compared to the base case, and naturally dark shades require less heating energy than white shades [table **4-16**].

In Seattle and Philadelphia, cooling energy savings benefit the most from white shades with a medium solar control (*WS_Sol378_ctr*) with the benefit dropping at a higher set point. The highest savings result from high solar control (*WS_Sol630_ctr*) with a white shade in Minneapolis.

In general, white shades perform slightly better overall providing savings that are about 1-3% more relative to the total energy than dark shades except on a south façade as indicated on table **4-16**.

Automatic control strategies comparison

The difference between two automatic control strategies, a time control strategy (*EMWA_ctr)* and a solar radiation control strategy *(Solxxx_ctr)* were studied.

An example case of Minneapolis with window D and WWR=0.40 is presented in table **4-17**. The table presents total energy savings for a space when these two automatic control strategies are applied. It shows that the solar radiation control strategy performs better than the time control strategy for both colors of shade except on the north side where the benefits are similar. This is due to the low solar radiation gains on the north orientation.

Optimizing control strategies

This section shows total energy savings optimization with building orientation, presented in figures **4-25** to **4-27** and appendix **A-18** to **A-20.** Three cases are selected in two cities with window D and WWR=0.40.

Table 4-16: Heating, cooling, lighting and total energy savings for solar radiation control strategies in Minneapolis across orientations for window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades.

North	*WS_189_ctr*	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
Heating	-8.3%	-8.1%	-8.0%	-8.1%	-8.1%	-8.1%
Cooling	21.8%	21.5%	20.8%	20.9%	21.2%	20.7%
Lighting	**81.3%**	**82.0%**	**82.0%**	**81.0%**	**82.0%**	**82.0%**
Total	11.6%	11.8%	11.8%	11.6%	11.8%	11.8%
South						
Heating	-17.5%	-16.9%	-7.9%	-4.5%	-6.5%	-8.0%
Cooling	24.7%	24.3%	16.2%	5.6%	10.8%	16.1%
Lighting	**60.0%**	**73.5%**	**73.5%**	**37.6%**	**56.8%**	**73.5%**
Total	5.9%	9.2%	13.6%	6.3%	10.0%	13.5%
East						
Heating	-11.2%	-10.7%	-8.5%	-6.6%	-7.7%	-8.6%
Cooling	26.1%	25.0%	15.7%	10.8%	13.2%	15.6%
Lighting	**78.4%**	**84.0%**	**81.2%**	**61.8%**	**72.6%**	**81.2%**
Total	11.2%	12.5%	12.1%	9.0%	10.7%	12.1%
West						
Heating	-9.4%	-9.0%	-7.5%	-5.9%	-6.9%	-7.5%
Cooling	22.4%	22.0%	14.1%	6.4%	9.7%	14.0%
Lighting	**64.5%**	**72.9%**	**73.0%**	**51.3%**	**63.2%**	**73.0%**
Total	9.0%	10.8%	10.9%	6.7%	8.8%	10.8%

Table 4-17: Annual total energy savings between different automatic control strategies and shade colors in Minneapolis.

Total	*EMWA_ WS _ctr*	*WS_ 189_ ctr*	*WS_ 378_ ctr*	*WS_ 630_ ctr*	*EMWA_D S _ctr*	*DS_ 189_ ctr*	*DS_ 378_ ctr*	*DS_ 630_ ctr*
West	8.29%	9.02%	**10.82%**	**10.87%**	5.59%	6.75%	8.77%	**10.80%**
East	10.38%	11.23%	**12.51%**	**12.15%**	8.15%	9.04%	10.69%	**12.09%**
North	**11.81%**	**11.57%**	**11.79%**	**11.83%**	**11.85%**	**11.60%**	**11.81%**	**11.77%**
South	3.65%	5.85%	**9.16%**	**13.59%**	2.54%	6.27%	**9.99%**	**13.52%**

The results show that the savings from these three control strategies are similar for the north façade. The east, west and south façades show higher total energy savings when used with high and medium solar control and white shades but only the high solar set point for dark shades, An exception is in Minneapolis where a high solar control with white and dark shades both work best.

If only one control strategy is to be applied to all orientations of a building, a high solar control strategy with white shades (*WS_Sol630_ctr*) should yield the maximum annual total energy savings [table **4-18**].

Table 4-18: Total energy savings in a cold climate, MN, PA and WA, with solar radiation control strategies and lighting control (*SolXXX_ctr*) for window D (SHGC=0.28/ U=1.61/ Tvis=0.64).

Philadelphia with window D, WWR=0.40, (PA_D_40)

	WS_189_ctr	WS_378_ctr	WS_630_ctr	DS_189_ctr	DS_378_ctr	DS_630_ctr
West	24.11%	26.90%	**28.21%**	19.50%	23.34%	27.01%
East	27.31%	28.73%	**29.40%**	24.07%	26.37%	28.19%
North	28.17%	28.44%	28.46%	28.01%	**28.47%**	**28.47%**
South	22.34%	26.93%	29.89%	19.21%	25.44%	**30.38%**

Minneapolis with window D, WWR=0.40, (MN_D_40)

	WS_189_ctr	WS_378_ctr	WS_630_ctr	DS_189_ctr	DS_378_ctr	DS_630_ctr
West	9.02%	10.82%	**10.87%**	6.75%	8.77%	10.80%
East	11.23%	**12.51%**	12.15%	9.04%	10.69%	12.09%
North	11.57%	11.79%	**11.83%**	11.60%	11.82%	11.76%
South	5.86%	9.16%	**13.59%**	6.27%	9.99%	13.52%

Seattle with window D, WWR=0.40, (WA_D_40)

	WS_189_ctr	WS_378_ctr	WS_630_ctr	DS_189_ctr	DS_378_ctr	DS_630_ctr
West	19.49%	22.66%	**23.96%**	14.34%	18.54%	21.62%
East	24.84%	26.82%	**26.86%**	20.58%	23.76%	25.71%
North	24.88%	25.20%	**25.25%**	24.85%	25.24%	**25.25%**
South	18.04%	23.62%	**26.25%**	12.84%	19.79%	25.11%

Light grey highlighted shows the maximum savings from white shades
Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix
D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)
20,40 - Window-to-wall ratio 0.20 to 0.40

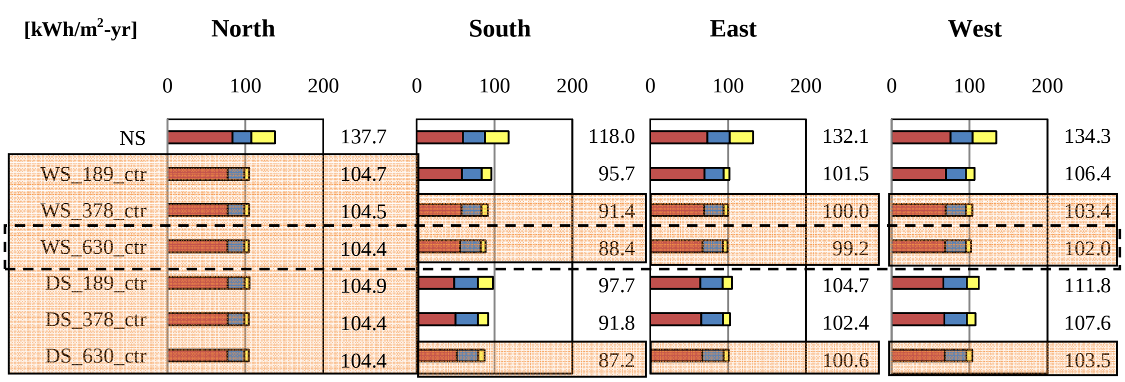


Fig 4-25: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Philadelphia, Window D (SHGC=0.27/ U=0.26/ Tvis=0.64), two shade colors and WWR of 0.40.

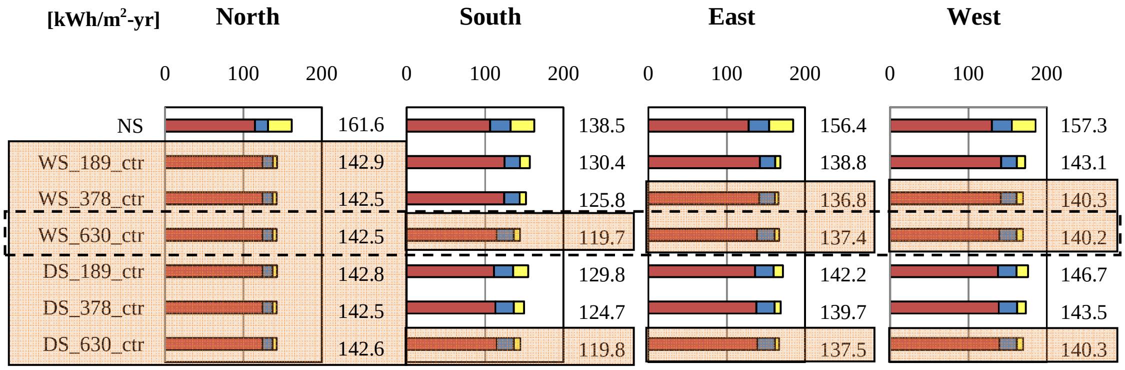


Fig 4-26: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Minneapolis, Window D (SHGC=0.27/ U=0.26/ Tvis=0.64), two shade colors and WWR of 0.40.

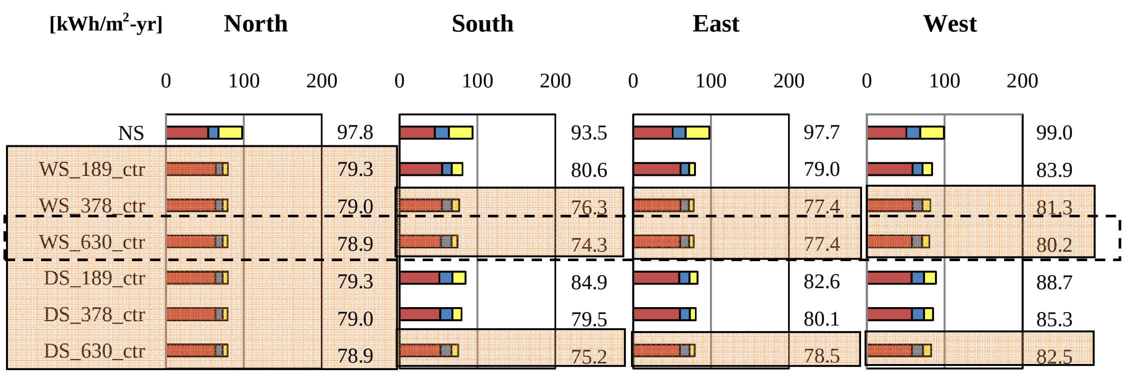


Fig 4-27: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Seattle, Window D (SHGC=0.27/ U=0.26/ Tvis=0.64), two shade colors and WWR of 0.40.

Heating Cooling Lighting

Highlighted area represents the strategies with low total energy use

The dotted line represents the recommended strategy that yields the maximum savings

4.3.2.2 Cooling-dominated climates

Impact on total energy savings

Table **4-19** presents total energy savings for solar radiation control strategies applied in Houston and Phoenix.

The total energy savings are in the range of 18-35% for Texas and 6-30% for Phoenix. Again, the high solar set point control strategy with a white shade (*WS_Sol630_ctr*) provides the maximum savings in all cases.

Table **4-20** shows that a north orientation provides no significant difference in total energy savings between the control strategies due to the absence of direct sunlight. The maximum percent total energy savings occurs on an east façade in all cases except with dark shades, where the north façade provides the highest percent savings. The west and south façades provide the lowest percent savings especially with dark shades and a low solar set point (*DS_Sol189_ctr)*. On the north and east facades, the differences in savings reach an optimum at a medium solar control strategy unlike the cold climate results. On the west and south exposures, the higher the solar set point, the greater the energy savings.

Impact on heating, cooling and lighting energy

Lighting savings provide greater contributions toward total energy savings than cooling energy savings as seen on table **4-19** and appendix **A-21** for Phoenix with window D and WWR=0.40.

For white shades, they show high cooling and lighting savings in the range of 9-14% and 60-87% respectively. Dark shades do not performed well in this region, although they still benefit cooling and lighting energy savings in the range of 1-10% and 30-86% respectively.

Automatic control strategies comparison

The difference between two automatic control strategies, a time control strategy and a solar radiation control strategy were studied.

An example case of Phoenix with window D and WWR 0.40 is presented below [Table **4-21**] for the time and solar setpoint automatic control strategies. It shows that the solar radiation control strategy performs slightly better than the time control strategy for both of shade colors.

Optimizing control strategies

This section shows total energy savings optimization across building orientations as presented in figures **4-28** to **4-29** and appendix **A-21** and **A-22.** Three cases are selected in two cities with window D and WWR=0.40.

Cooling energy use is the dominant portion in this region. It is clear that the optimum control strategy for this region should minimize solar gain hours, which occurs when shades are applied with low solar control. However, a high solar set point with white shades (*WS_Sol630_ctr*) shows the highest total energy savings compared to other controls. This is because the lighting savings, although small, contribute more toward the total energy savings than do cooling energy savings. The second best control strategy for Phoenix is a medium solar control with a white shade (*WS_Sol378_ctr*).

If only one control strategy is to be applied to all orientations of a building, a high solar set point with white shades (*WS_Sol630_ctr*) yielded the maximum annual total energy savings [table **4-21**].

Table 4-19: Heating, cooling, lighting and total energy savings for solar radiation control strategies in Phoenix across orientations with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades.

North	*WS_189_ctr*	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
Heating	-38.9%	-38.2%	-37.1%	-37.5%	-37.2%	-36.7%
Cooling	10.4%	10.3%	9.9%	9.3%	10.1%	9.8%
Lighting	82.5%	85.6%	85.6%	81.1%	85.6%	85.6%
Total	**29.5%**	**30.5%**	**30.3%**	**28.5%**	**30.3%**	**30.2%**
South						
Heating	-131.3%	-129.4%	-118.1%	-86.1%	-93.1%	-100.0%
Cooling	13.5%	13.4%	10.9%	-1.2%	2.0%	4.5%
Lighting	59.2%	76.1%	83.9%	31.0%	54.2%	72.2%
Total	**23.7%**	**28.3%**	**28.8%**	**6.2%**	**14.8%**	**21.4%**
East						
Heating	-56.2%	-55.7%	-47.0%	-30.9%	-37.3%	-44.8%
Cooling	14.7%	14.1%	11.5%	3.5%	4.7%	6.3%
Lighting	80.5%	85.9%	86.9%	57.8%	67.6%	79.0%
Total	**30.4%**	**31.5%**	**30.2%**	**17.2%**	**20.5%**	**24.5%**
West						
Heating	-56.2%	-53.6%	-44.8%	-46.6%	-46.5%	-43.1%
Cooling	12.2%	12.2%	10.5%	0.4%	2.2%	5.0%
Lighting	69.3%	77.8%	83.3%	47.6%	59.2%	73.5%
Total	**25.2%**	**27.6%**	**28.3%**	**11.5%**	**16.0%**	**21.9%**

Table 4-20: Annual total energy savings between different automatic control strategies and shade colors in Phoenix.

	EMWA_ WS _ctr	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*EMWA_ DS_ctr*	*DS_189_ ctr*	*DS_378_ ctr*	*DS_630_ ctr*
West	24.52%	28.72%	31.48%	32.08%	11.47%	18.53%	24.14%	29.56%
East	27.72%	34.74%	36.22%	35.13%	14.32%	24.44%	29.27%	33.29%
North	30.12%	34.84%	35.19%	35.05%	30.11%	34.36%	35.14%	35.04%
South	17.08%	28.18%	33.47%	34.06%	-1.94%	16.15%	26.18%	30.91%

Table 4-21: Total energy savings in hot climates, TX, and AZ, with solar radiation control strategies, lighting control (*SolXXX_ctr*) and window D (SHGC=0.27/ U=0.26/ Tvis=0.64).

Houston with window D, WWR=0.40, (TX_D_40)

	WS_189_ctr	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
West	28.72%	31.48%	**32.08%**	18.53%	24.14%	**29.56%**
East	34.74%	36.22%	**35.13%**	24.44%	29.27%	**33.29%**
North	34.84%	35.19%	**35.05%**	34.36%	35.14%	**35.04%**
South	28.18%	33.47%	**34.06%**	16.15%	26.18%	**30.91%**

Phoenix with window D, WWR=0.40, (AZ_D_40)

	WS_189_ctr	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
West	25.20%	27.63%	**28.30%**	11.55%	15.97%	**21.94%**
East	30.37%	31.47%	**30.20%**	17.22%	20.52%	**24.48%**
North	29.54%	30.46%	**30.28%**	28.50%	30.35%	**30.21%**
South	23.73%	28.28%	**28.83%**	6.23%	14.76%	**21.38%**

Light grey highlighted shows the maximum savings from white shades

Dark grey highlighted shows the maximum savings from dark shades

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix

D – Window (A standard Low E spectral reflective double glazing, (SHGC=0.28/ U=1.61/ Tvis=0.64)

20,40 - Window-to-wall ratio 0.20 to 0.40

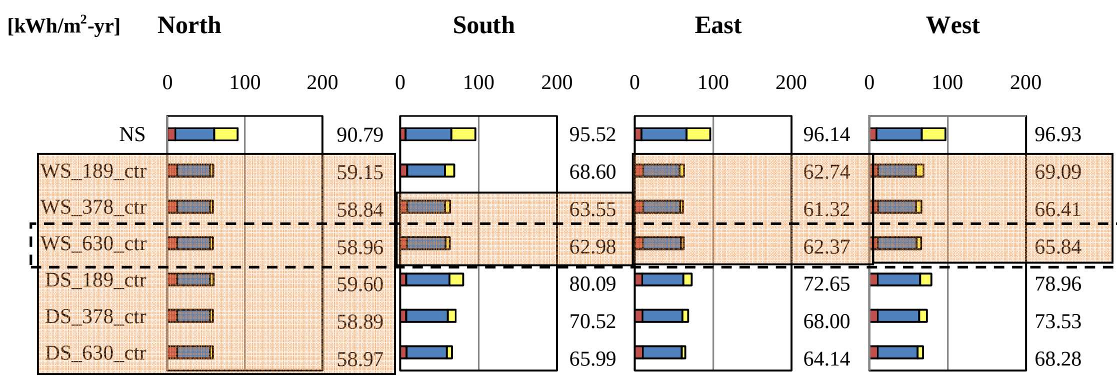


Fig 4-28: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Houston, Window D (SHGC=0.28/ U=1.61/ Tvis=0.64), two shade colors and WWR of 0.40.

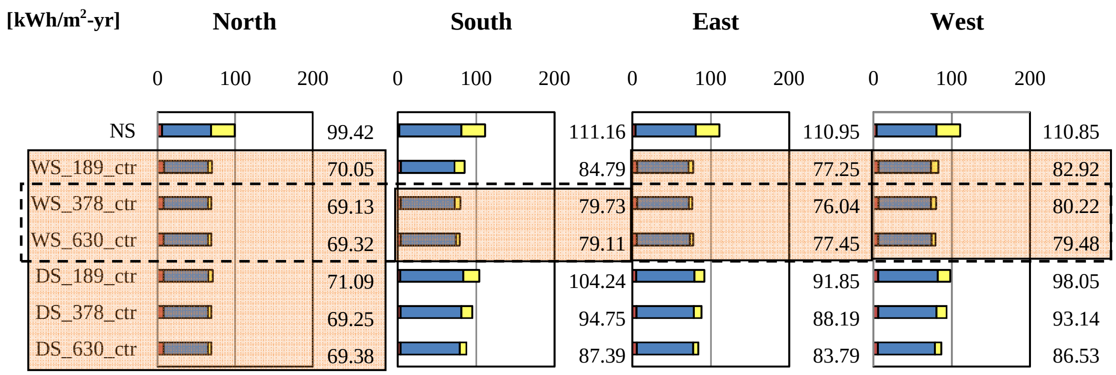
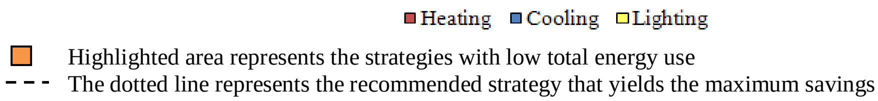


Fig 4-29: Annual total energy (heating, cooling and lighting energy) across orientations and different control strategies: Phoenix, Window D (SHGC=0.28/ U=1.61/ Tvis=0.64), two shade colors and WWR of 0.40.



4.4 Conclusions

From the results in the previous sections, a number of conclusions can be drawn.

On a building level with a standard non Low-E window (window A) and different geometries:

- **Shades closed all day without lighting control**

The use of shades closed all day can provide a small amount of savings in heating and cooling energy, 1-5% in a cold climate and about 8-12% in a hot climate for WWR=0.40. For WWR=0.20, 0.25-1.4% and 4.5-6% total energy savings is achieved in a cold and hot climate respectively. For WWR=0.40, heating energy savings only occur with the use of dark shades while cooling energy savings occur for only white shades. For WWR=0.20, heating energy savings also occur with dark shades while cooling energy savings occur for both white and dark shades. A long thin building facing east and west on its long exposure provides the highest savings with white shades closed all day but consume more energy than the other building configuration studied.

- **Envelope loads, internal gains and seasonal effects**

White shades significantly reduce solar heat gain during summer months. Thus, with larger window areas as in a long thin building (E-W), the impact of shades is more pronounced. A long thin building facing E-W shows the highest total energy use per area (kWh/m^2), and also the highest savings. White shades, when used in summer, increase cooling energy savings due to the reduction of transmitted solar load through the windows. Dark shades help reduce glazing losses and increase solar heat gains which benefit the winter months. However, the total savings received from the dark shades show a little benefit over the base case due to the loss in cooling savings during summer months when compared to the use of white shades.

If white shades are left open during winter months and closed during summer months, total energy savings are increased from 2.78% to 5.20% for a cold climate. This is due to reduced heat loss while requiring about the same amount of cooling energy when compared to shades that are closed all day all year long. In a hot climate, the savings for white and dark shades, when used all year, are 16.36% and 7.03%. While the savings for white shades, when used only in the summer, reduce to 6.73% with dark shades showing a loss in energy. However, the savings are still large when compared to those obtained from the cold climate.

- **Shades closed all day with lighting control**

The use of a shade closed all day with lighting control shows total energy savings for a cold climate about at 6-11% with 16-19% for a hot climate for WWR=0.40. The highest portion of savings comes from cooling with 8-11% for a cold climate and 14-16% for a hot climate out of the total energy savings. The second largest portion is from lighting savings with about 3-4% for both climates. A long thin E-W building, again, shows the highest total energy savings compared to the other geometries.

- **Building Zones**

When the perimeter zone is applied with shades and lighting control, it showed that for white shades, lighting energy savings of 42.74%, 45.12% and 46.91% occur on a long thin E-W, a long thin N-S and a square building respectively. And the cooling energy savings in perimeter zone is at 34.19%, 35.56% and 35.89% compared to the base case without shades for a long thin E-W, a square and a long thin N-S respectively.

On a test space level:

The test space level study can be separated into 2 parts. The first part consists of the study of basic control strategies such as a shade closed all day with and without lighting control (*DN, DN_ctr*).

The second part consists of further investigations on a time control strategy with lighting control (*EMWA_ctr*) and a solar radiation control strategy (*Solxxx_ctr*) geared towards more automated control of shades.

- **Shades closed all day and automatic time control strategies with and without lighting control**

White shades perform better than dark shades overall, although dark shades can provide savings similar to white shades with a time control strategy.

For control strategies, a time control strategy with lighting control and a white shade (*EMWA_ctr*) shows the best overall performance when compared to other strategies such as shades closed all day and provide the maximum total energy savings in all cities.

The differences in total energy savings for each building orientation are shown in Table **4-22**.

Table 4-22: Energy savings for each façade with a time control strategy (*EMWA*) with white shades.

	Philadelphia	Minneapolis	Seattle	Houston	Phoenix
North	14-17%	7-22%	16-22%	30-35%	28-35%
South	1-11%	1-4%	4-11%	7-24%	8-17%
East	10-15%	5-10%	7-15%	23-33%	18-31%
West	9-13%	3-12%	8-15%	15-28%	13-28%

The results show that different orientations can provide different energy savings with the highest savings occurring on the north facade, followed by the east and west. The least savings occur on the south façade. Although for the north façade, shades are left opened all the time with the use of a time control strategy. Shades closed all day both with and without lighting control works well in a hot climate. With shades closed all day, the savings are affected by the WWRs. By increasing the size of the window (WWR), the savings increase proportionally. The size of window, however, did not significantly affect the change in savings when used with a time control strategy.

Figure **4-30** shows the impact on energy savings of the higher performance window, window D (Low-E windows) when compared to the base case with standard double pane clear glazing (window A) for Minneapolis and Phoenix. When windows are changed, an energy savings of 8-25% across all orientations is already realized without the impact of shades. Shades help provide additional savings on top of the savings received from the better window. The additional shade savings range from 1-30% depending on the control strategies.

The total energy savings is mainly contributed from **lighting energy savings (10-28%).** Cooling energy savings (6-10%) also contributes to the overall total energy savings but to a lesser degree [figures **4-31** to **4-33**].

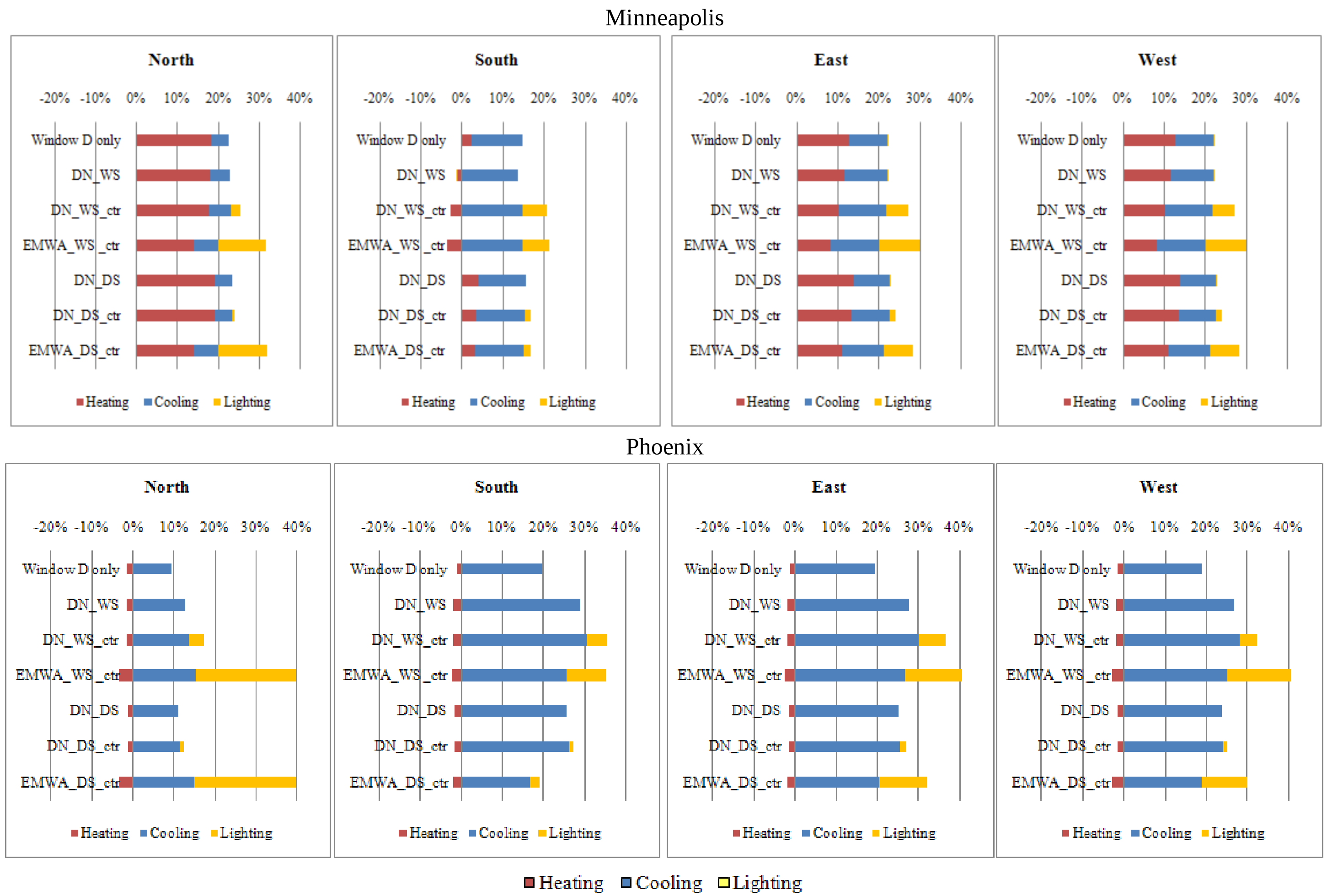


Figure 4-30: Heating, cooling and lighting energy savings for window D and WWR=0.40 for different cities for shades closed all day and time control strategies when compared to a base case of window A with no shade and lighting control.

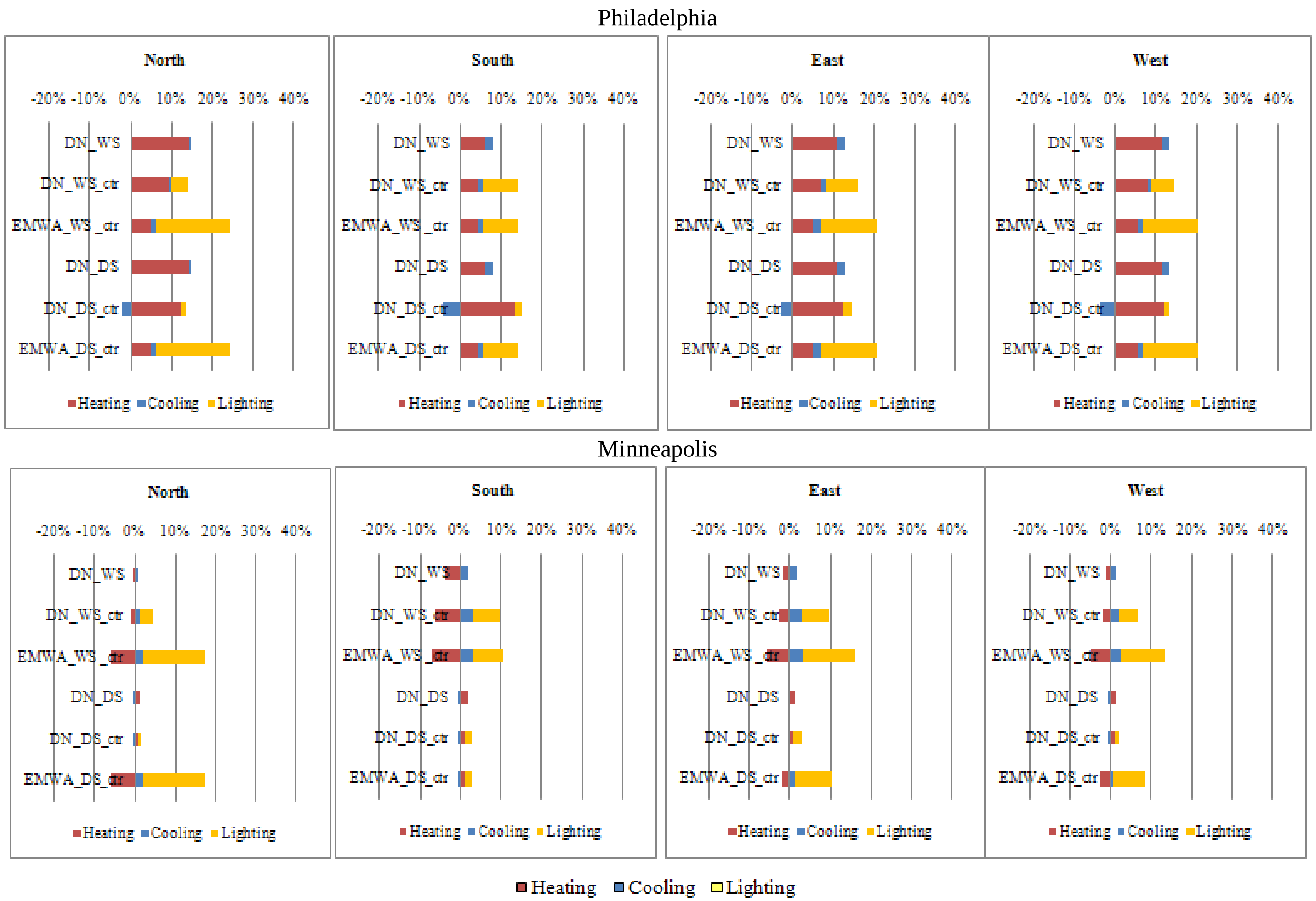


Figure 4-31: Heating, cooling and lighting energy savings for window D and WWR=0.40 for Philadelphia and Minneapolis for shades closed all day and time control strategies.

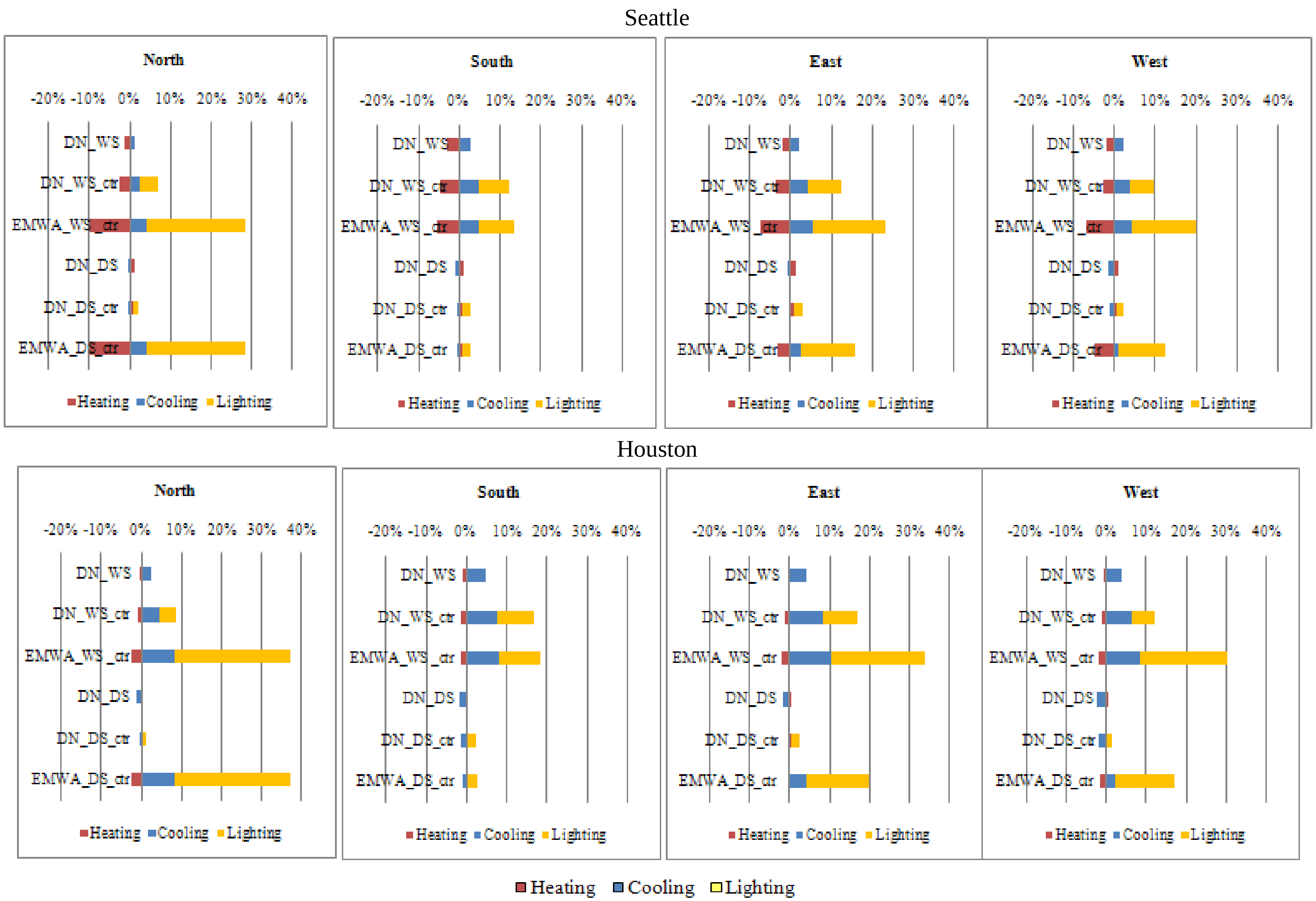


Figure 4-32: Heating, cooling and lighting energy savings for window D and WWR=0.40 for Seattle and Houston for shades closed all day and time control strategies.

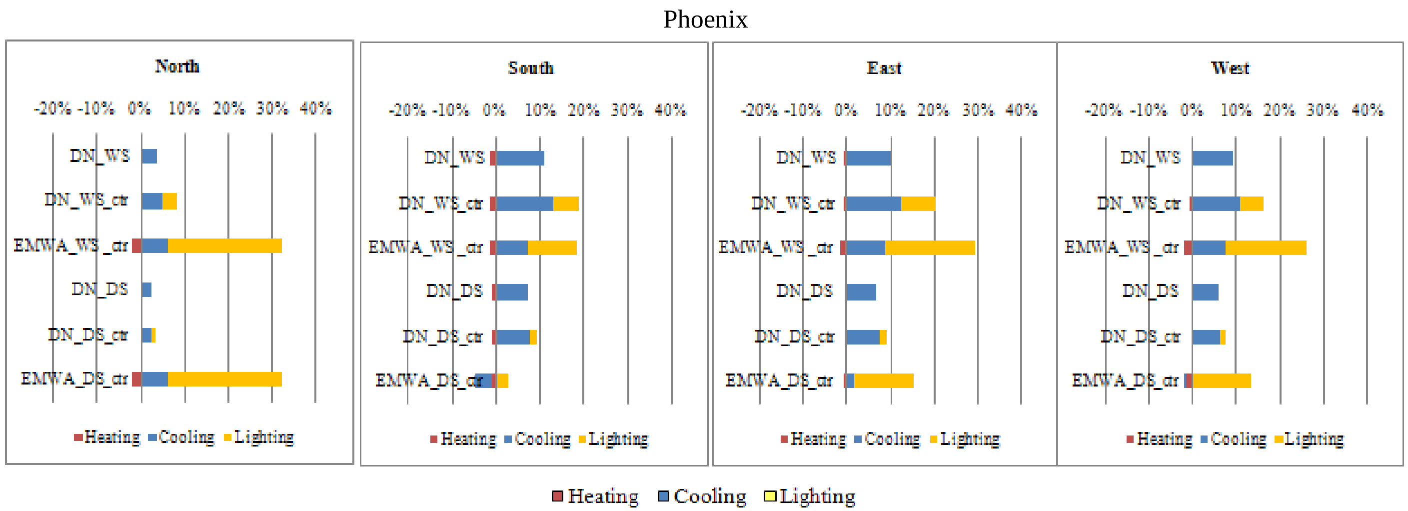


Figure 4-33: Heating, cooling and lighting energy savings for window D and WWR=0.40 for Phoenix for shades closed all day and time control strategies.

Automatic solar radiation control strategies with lighting control systems

Solar radiation control strategies are analyzed with window D and a WWR of 0.40 to optimize the total energy savings.

For shade properties, white shades perform better than dark shades overall, although dark shades can provide savings similar to white shades with a high solar control strategy.

For control strategies, a high solar control strategy is the most appropriate control to consider with white shades in all cities. The lower solar control set points also show good performance with similar but lower total energy savings compared to the high set point.

Again, lighting energy savings contributes more to total energy savings than cooling or heating savings.

Different orientations show different energy savings with east and west windows showing a similar trend in how they react to the solar radiation control with the highest set points providing greater savings. North-facing shows similar trends throughout the different set points.

The south-facing windows show slightly lower lighting energy savings compared to the other orientations.

Figures **4-34** to **4-36** show that by using a solar radiation control strategy, the lighting energy savings are maximized compared to figures **4-31** to **4-33** for shades closed all day and a time control strategy. A solar radiation control strategy gives better performance over a time control strategy with an overall increase in savings as shown in tables **4-23** and **4-24**.

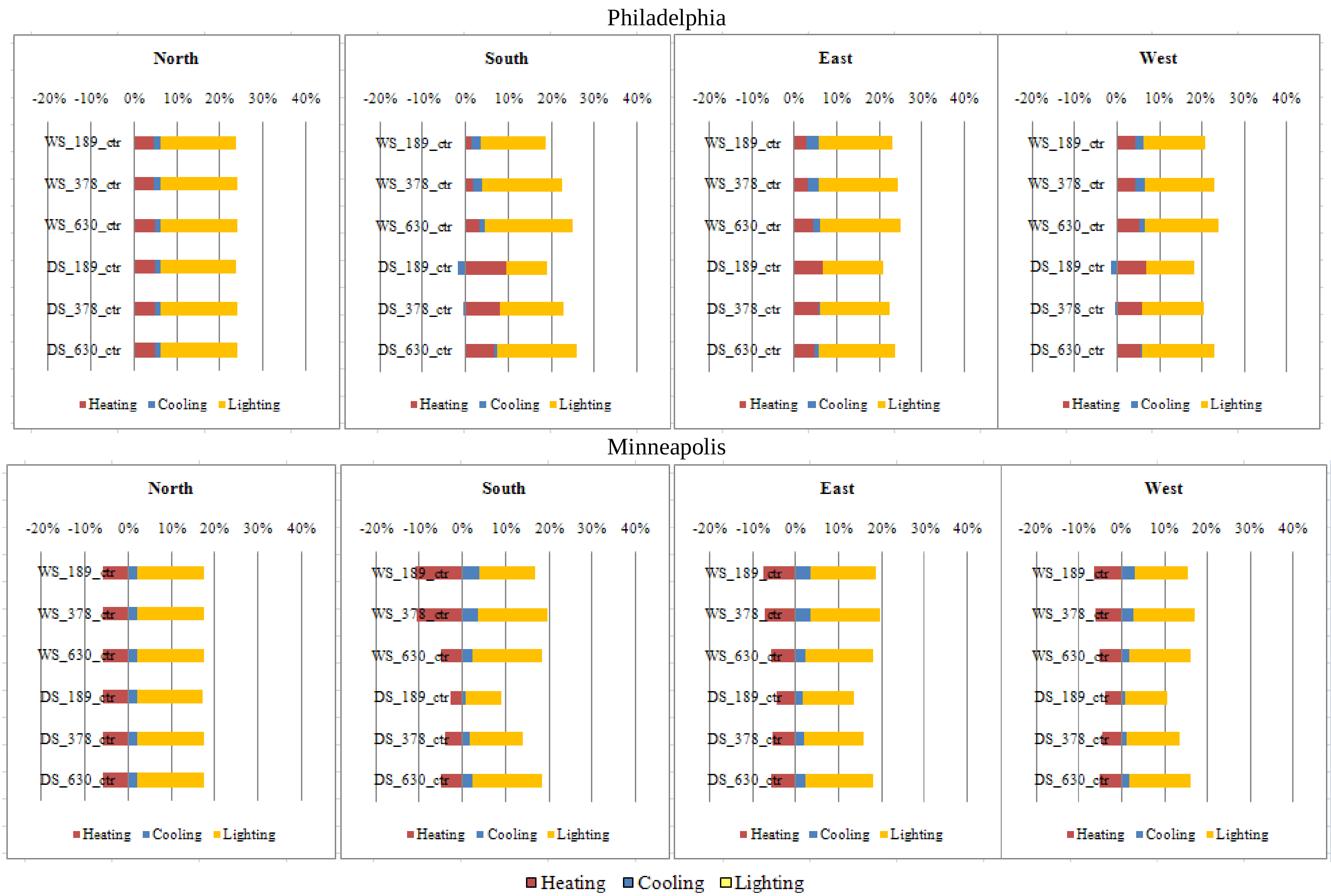


Figure 4-34: Heating, cooling and lighting energy savings for window D and WWR=0.40 for Philadelphia and Minneapolis for shades closed all day and solar radiation control strategies.

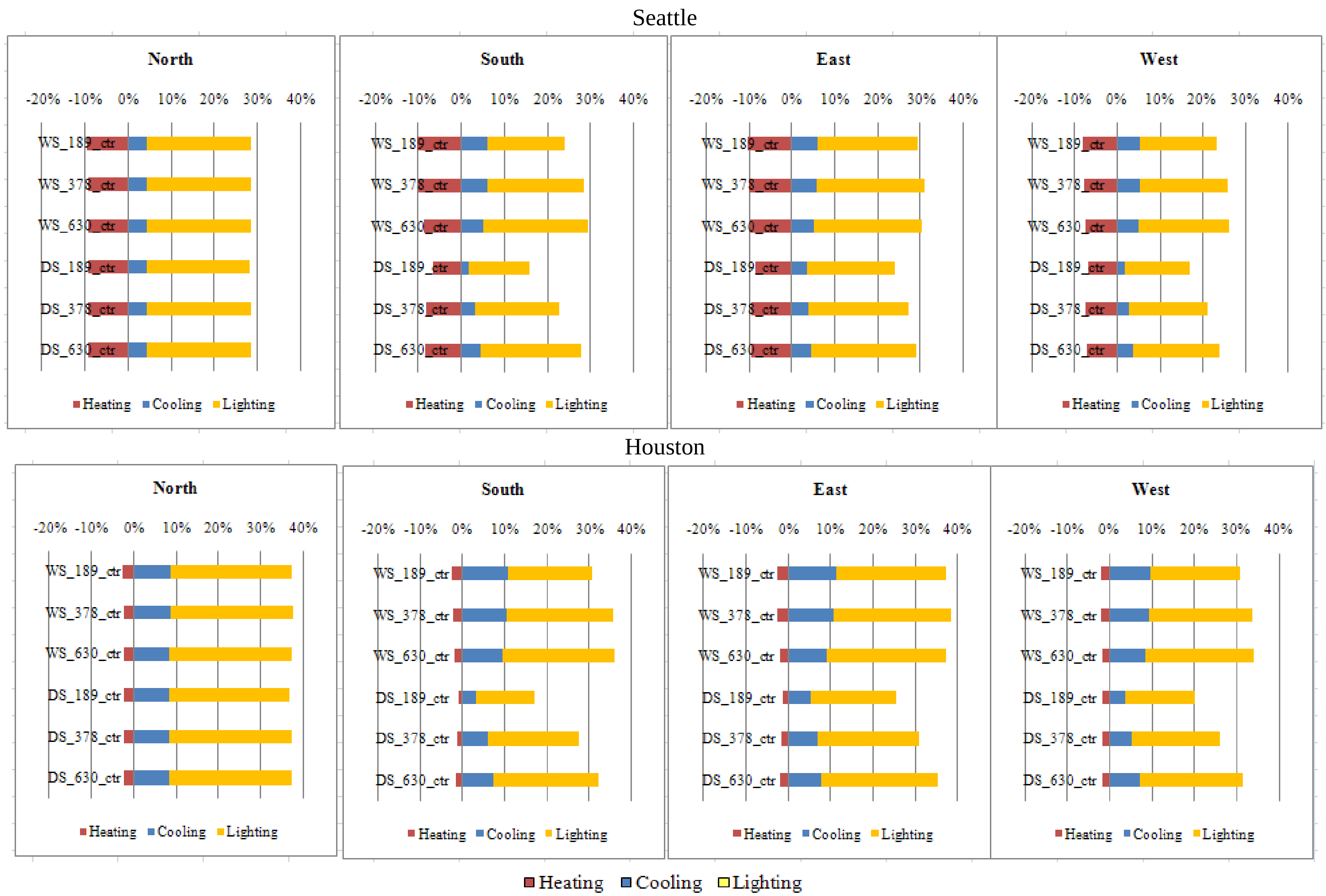


Figure 4-35: Heating, cooling and lighting energy savings for window D and WWR=0.40 in Seattle and Houston for shades closed all day and solar radiation control strategies.

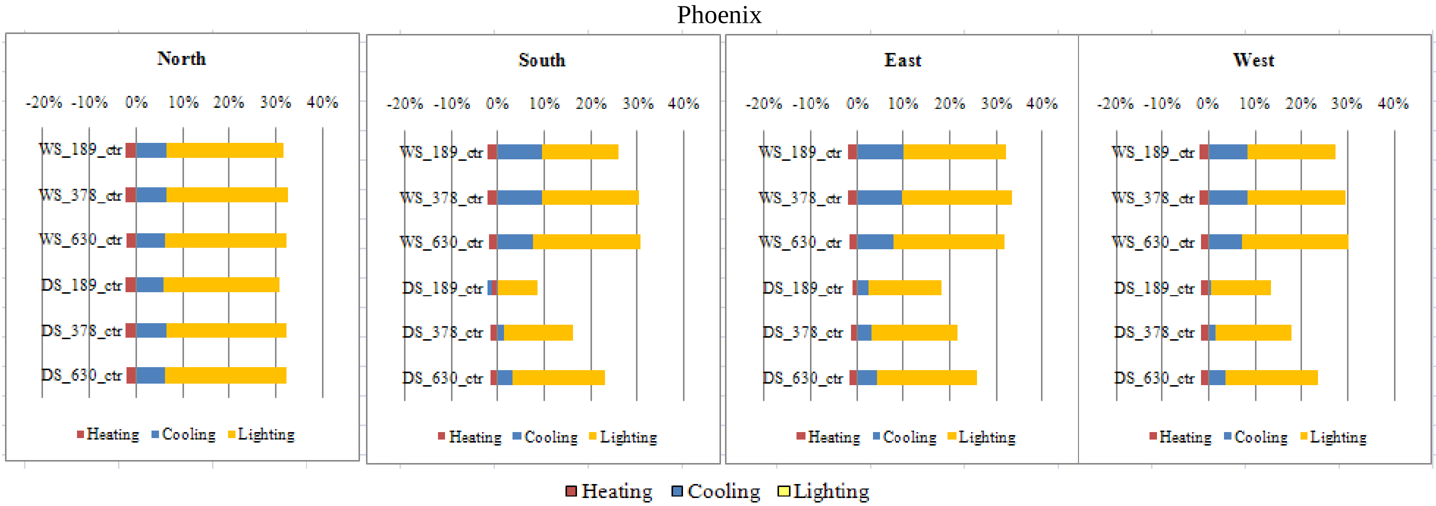


Figure 4-36: Heating, cooling and lighting energy savings for window D and WWR=0.40 in Phoenix for shades closed all day and solar radiation control strategies.

Table 4-23: Annual energy use and percent increase of a solar control strategy over a time control strategy with window D, WWR=0.40, white shades on different orientations.

kWh/m^2	EMWA_WS_ctr				WS_Sol630_ctr			
	North	South	East	West	North	South	East	West
Philadelphia	104.46	101.08	104.67	107.11	104.43	88.39	99.15	102.05
Minneapolis	142.49	133.47	140.14	144.23	142.47	119.7	137.37	140.17
Seattle	79.47	86.36	82.18	86.1	78.94	74.25	77.42	80.25
Houston	59.34	79.41	65.53	69.54	58.96	62.98	62.37	65.84
Phoenix	69.47	92.18	80.19	83.67	69.32	79.11	77.45	79.48

For south orientations, solar radiation control performs better than the time control by about 10-20% and on the east and west façade, it is about 2-7% better. For the north side, both automatic control strategies show similar performance because there is less direct sunlight on the north side.

Table 4-24: Annual energy use and percent increase of a solar control strategy over a time control strategy with window D, WWR=0.40, white shades on different orientations.

	North	South	East	West
Philadelphia	0.0%	12.6%	5.3%	4.7%
Minneapolis	0.0%	10.3%	2.0%	2.8%
Seattle	0.7%	14.0%	5.8%	6.8%
Houston	0.6%	20.7%	4.8%	5.3%
Phoenix	0.2%	14.2%	3.4%	5.0%

The higher the solar set point, the higher the overall total energy savings. The best performance occurs with white shades and a high solar set point control strategy (*WS_Sol630_ctr*).

The different savings across orientations are shown below in table **4-25.** The north orientation gives smaller percent savings due to no difference in the amount of time that shades are applied.

Table 4-25: Energy savings via each façade in each city with a high solar setpoint control strategy and white shades.

	Philadelphia	Minneapolis	Seattle	Houston	Phoenix
North	28%	12%	25%	34-35%	29-30%
South	19-30%	6-14%	13-26%	16-34%	6-29%
East	24-29%	9-13%	21-27%	24-36%	17-31%
West	20-28%	7-11%	14-23%	19-32%	12-28%

4.5 References

Sullivan, R., E. S. Lee, et al. (1994). "Effect of switching control strategies on the energy performance of electrochromic windows." Proceedings of SPIE - The International Society for Optical Engineering **2255**: 443-455.

Chapter 5

COMBINING VISUAL QUALITY AND ENERGY SAVINGS

This chapter presents a variety of control strategies and their impact on both visual quality and energy savings. The automatic shade control strategies in this chapter were developed with the criteria to eliminate direct sunlight, to allow a variety of different levels of sunlight penetration and to provide acceptable values of illuminance, glare, luminance ratios and view hours.

Visual quality is assessed using several indices such as the daylight glare index (DGI), the work plane illuminance, the luminance ratios and the view hours.

This chapter also provides a comparison of the shade control strategies previously presented in chapter 4. The goal is to provide a recommendation for the most suitable shade control strategies to optimize both energy savings and visual quality.

5.1 The development of automatic control strategies to maximize lighting savings and provide acceptable visual quality

As mentioned in chapter 4, lighting energy savings dominate total energy savings with the use of automatic lighting control. Lighting savings mostly occur when the shades are open and provide higher interior daylight levels. Hence, automatic shade control strategies with lighting control were developed with the goal to maximize lighting energy savings and achieve acceptable visual quality. The concepts behind the development of each control strategy are:

1) Limit or eliminate sunlight penetration beyond a distance of 0.60 m (2ft) from the windows on all surfaces.
2) Improve total energy savings, especially lighting energy savings, by leaving the shades open as much as possible without negatively affecting visual quality. In order to do so, the exterior direct normal illuminance is used to regulate the shades.
3) Maintain the interior illuminance level at a critical point on the work plane below a useful illuminance level. The recommended range for daylight illuminance is between 100 and 2000 lux (10 to 200 fc).
4) Reduce the number of hours with poor visual quality. In this study, daylight glare index (DGI) and luminance ratios were considered.

5) Maximize the number of view hours achieved (i.e. hours when the shade is up)

All of these criteria are used in the development of automatic control strategies but not necessary combined.

The automatic control strategies that are based on the above criteria are as follows:

- **Sunlight penetration control (*A_pA_z_ctr*):** This method controls the shades so no direct sunlight penetrates beyond a 0.6m (2ft) distance. Shades are fully closed when the profile angle (A_p) is between 0 and 72 degrees and the building elevation azimuth angle (A_z) is less than 67 and 72 degrees for WWR 0.20 and 0.40 respectively regardless of the cloud cover condition [Figure **5-1**].

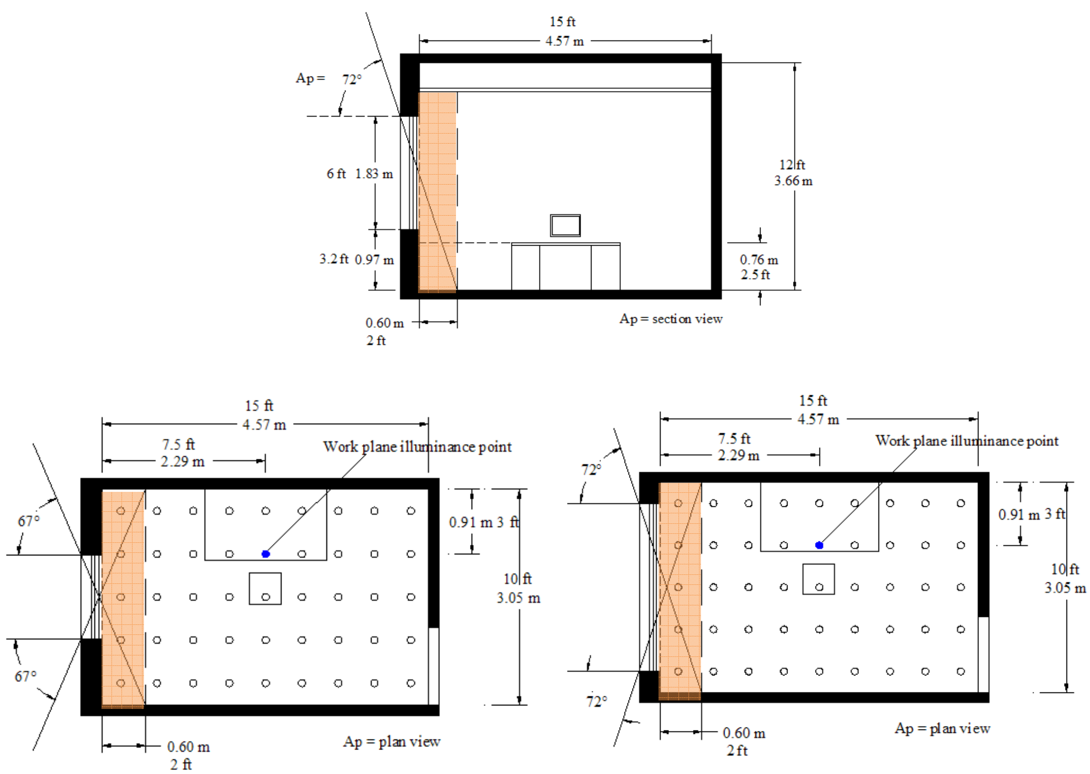


Fig 5-1: Profile angle (A_p) (above), and solar elevation azimuth angle (A_z) (below) dictate shade position (limiting direct sunlight to shaded area) for WWR 0.20 (below left) and 0.40 (below right).

For all five cities, hourly profile angles (A_p) and building elevation azimuth angles (A_z) are calculated for the entire year at the building site. Then, they were input into the shade control algorithm.

An example of the sunlight penetration control strategy (*A_pA_z_ctr)* is shown in tables **5-1** and **5-2** for a single test day for west and south orientations in Minneapolis. The shaded areas show times when the shades would be closed. A value of one for the shade control algorithm (column 6) represents a closed shade when both profile control (column 4) and building elevation azimuth control (column 5) are both equal to 1, indicating sunlight penetration would occur beyond 0.6m (2ft). Otherwise, the shades are fully open.

From the example, for a west-facing window, shades are closed for 4 hours during the 2 pm to 5 pm daylight blocks (actual hour 2:30-4:30 pm), while for a south-facing window, the shades are closed for 10 hours during the 8 am to 5 pm time blocks.

Table 5-1: An example of hourly configurations of shade for west-facing windows with white shades on Jan 23rd in Minneapolis: a control value of 1 represents a closed shade and a value of 0 represents a fully opened shade.

Date/Time	Profile angles (A_p)	Solar elevation azimuth angle (A_z)	Profile control	Building elevation azimuth control	Shade control algorithm
01/23 01:00:00	No sun	No sun	0	0	0
01/23 02:00:00	No sun	No sun	0	0	0
01/23 03:00:00	No sun	No sun	0	0	0
01/23 04:00:00	No sun	No sun	0	0	0
01/23 05:00:00	No sun	No sun	0	0	0
01/23 06:00:00	No sun	No sun	0	0	0
01/23 07:00:00	No sun	No sun	0	0	0
01/23 08:00:00	177.73	-149.40	0	0	0
01/23 09:00:00	166.00	-138.07	0	0	0
01/23 10:00:00	151.37	-125.46	0	0	0
01/23 11:00:00	131.20	-111.40	0	0	0
01/23 12:00:00	102.93	-96.19	0	0	0
01/23 13:00:00	70.59	-80.60	1	0	0
01/23 14:00:00	44.02	-65.58	1	1	1
01/23 15:00:00	25.26	-51.82	1	1	1
01/23 16:00:00	11.40	-39.49	1	1	1
01/23 17:00:00	0.06	-28.39	1	1	1
01/23 18:00:00	No sun	No sun	0	1	0
01/23 19:00:00	No sun	No sun	0	1	0
01/23 20:00:00	No sun	No sun	0	1	0
01/23 21:00:00	No sun	No sun	0	1	0
01/23 22:00:00	No sun	No sun	0	1	0
01/23 23:00:00	No sun	No sun	0	1	0
01/23 24:00:00	No sun	No sun	0	0	0

Table 5-2: An example of hourly configurations of shade for south-facing windows with white shades on Jan 23rd in Minneapolis: A control value of 1 represents a closed shade and a value of 0 a fully opened shade.

Date/Time	Profile angles (A_p)	Building elevation azimuth angle (A_z)	Profile control	Building elevation azimuth control	Shade control value
01/23 01:00:00	No sun	No sun	0	0	0
01/23 02:00:00	No sun	No sun	0	0	0
01/23 03:00:00	No sun	No sun	0	0	0
01/23 04:00:00	No sun	No sun	0	0	0
01/23 05:00:00	No sun	No sun	0	0	0
01/23 06:00:00	No sun	No sun	0	0	0
01/23 07:00:00	No sun	-69.94	0	1	0
01/23 08:00:00	3.73	-59.56	1	1	1
01/23 09:00:00	15.53	-48.27	1	1	1
01/23 10:00:00	21.32	-35.68	1	1	1
01/23 11:00:00	24.22	-21.64	1	1	1
01/23 12:00:00	25.42	-6.43	1	1	1
01/23 13:00:00	25.30	9.18	1	1	1
01/23 14:00:00	23.85	24.23	1	1	1
01/23 15:00:00	20.55	38.02	1	1	1
01/23 16:00:00	14.01	50.36	1	1	1
01/23 17:00:00	0.52	61.46	1	1	1
01/23 18:00:00	No sun	No sun	0	1	0
01/23 19:00:00	No sun	No sun	0	0	0
01/23 20:00:00	No sun	No sun	0	0	0
01/23 21:00:00	No sun	No sun	0	0	0
01/23 22:00:00	No sun	No sun	0	0	0
01/23 23:00:00	No sun	No sun	0	0	0
01/23 24:00:00	No sun	No sun	0	0	0

- **Direct normal illuminance control (*DIR2500_ctr* and *DIR5000_ctr*):** These control strategies adjust the shades based on sunlight penetration, as in A_pA_z control, but open the shades when the direct normal exterior illuminance is below 2500 lux (*DIR2500_ctr*) and 5000 lux (*DIR5000_ctr*) respectively, as the sky conditions approach overcast.
- **Work plane illuminance control (*Ewp_ctr*):** This control strategy applies the shades to reduce daylight levels within the space when the interior illuminance exceeds 2000 lux at the critical work plane point.

The number of hours the shades are in use for these different control strategies is shown in table **5-3**.

Table 5-3: The number of shade use hours under different control strategies for the west and south-facing windows in the five test cities.

Cities	Control type	South (hours)	West (hours)
Philadelphia	*Ap_Az_ctr*	2,561	1,711
	DIR 2500_ctr	1,806	1,346
	DIR 5000_ctr	1,883	1,290
	Ewp_ctr	1,162	880
Minneapolis	*Ap_Az_ctr*	2,954	1,721
	DIR 2500_ctr	2,297	1,371
	DIR 5000_ctr	2,243	1,296
	Ewp_ctr	1,318	882
Seattle	*Ap_Az_ctr*	2,954	1,717
	DIR 2500_ctr	1,816	1,304
	DIR 5000_ctr	1,926	1,218
	Ewp_ctr	955	754
Houston	*Ap_Az_ctr*	2,160	1,774
	DIR 2500_ctr	1,487	1,408
	DIR 5000_ctr	1,538	1,331
	Ewp_ctr	893	1,045
Phoenix	*Ap_Az_ctr*	2,293	1,826
	DIR 2500_ctr	2,020	1,753
	DIR 5000_ctr	2,067	1,711
	Ewp_ctr	1,240	1,243

Visual quality and energy performance report

The hourly control configurations were then applied in EnergyPlus as a time schedule for the test cases. The data are collected from the hourly simulation results including: work plane illuminance and daylight glare index (DGI) at the reference point.

Heating, cooling, lighting and total energy use and savings are reported annually for all test cases in west and south-facing offices with window D (SHGC=0.28/ U=1.61/ Tvis=0.64) and WWR=0.40.

The measurement point is shown in figure **5-2**. The work plane illuminance and hourly shade configurations for each control strategy are presented in table **5-4** for south-facing windows on Jan 23rd in Minneapolis, MN, which is a relatively cloudy winter day. A control value of 1 represents a closed shade and a value of 0 a fully opened shade. The work plane illuminance value is measured at a 0.76m (2.5 ft) height, 2.2 m (7.2 ft) from the window, and 0.91m (3ft) from the wall.

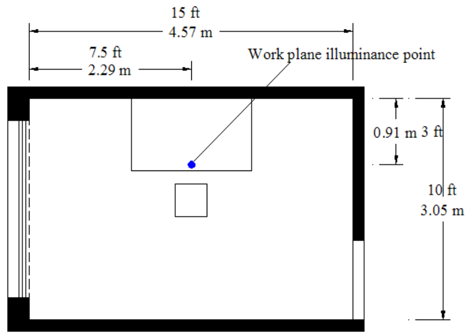


Figure 5-2: Work plane illuminance point in the test space (blue dot).

When shades are closed during all hours, sunlight penetration control (*ApAz_ctr*) results in 10 hours of shade use. Direct normal illuminance control reduces the shade use time to 5 and 3 hours for *DIR 2500_ctr* and *DIR 5000_ctr* respectively. Table **5-4** also shows differences in work plane illuminance and daylight glare index (DGI) for the shade up and down positions. In this table, since the illuminance on the work plane does not exceed 2000 lux on this day, the work plane illuminance control (*Ewp_ctr*) shows no use of shades. When shades are lowered, there is a significant drop in the work plane illuminance to about 10 to 15% of the original value. The results also show that the DGI is improved by the use of shades. For example, from 1-3pm, the DGI drops from above 22.0 (the recommended value for DGI is less than 22.0) to below 20.0.

Table 5-4: An example of shade hourly configurations of an all-day closed shade and automatic shade control strategies for south-facing windows with white shades on Jan 23rd in Minneapolis, overcast sky.

	Closed all day	Automatic control				Without white shade		With white shade	
Date and Time	*DN*	*ApAz _ctr*	*DIR 2500 _ctr*	*DIR 5000 _ctr*	*Ewp_ ctr*	Work plane illuminance (lux)	DGI	Work plane illuminance (lux)	DGI
07:00:00	1	0	0	0	0	0.00	0.0	0.00	0.0
08:00:00	1	1	1	1	0	43.51	7.2	6.15	0.2
09:00:00	1	1	1	0	0	475.70	17.0	77.19	6.2
10:00:00	1	1	1	1	0	1092.52	18.8	158.81	11.4
11:00:00	1	1	1	0	0	1194.32	19.0	160.10	13.7
12:00:00	1	1	0	0	0	1687.97	21.0	177.09	15.6
13:00:00	1	1	0	0	0	1869.51	22.7	184.88	16.3
14:00:00	1	1	0	0	0	1773.22	23.6	172.88	18.0
15:00:00	1	1	0	0	0	1357.84	23.8	142.23	19.4
16:00:00	1	1	0	0	0	832.88	20.7	93.56	20.5
17:00:00	1	1	1	1	0	237.98	6.0	28.08	6.0
18:00:00	1	0	0	0	0	0.00	0.0	0.00	0.0
total hours	**12**	**10**	**5**	**3**	**0**				

5.2 Energy savings analysis

5.2.1 Impact of shades on lighting energy savings for shades closed all day (*DN_ctr*) with lighting control and three automatic shade control strategies (*ApAz_ctr, DIR_ctr, Ewp_ctr*) with lighting control

The results of full-time shade implementations and three automatic control strategies are presented in this section. Window D (SHGC=0.28/ U=1.61/ Tvis=0.64) with a WWR of 0.40 and both white (*WS*) and dark shades (*DS*) are used.

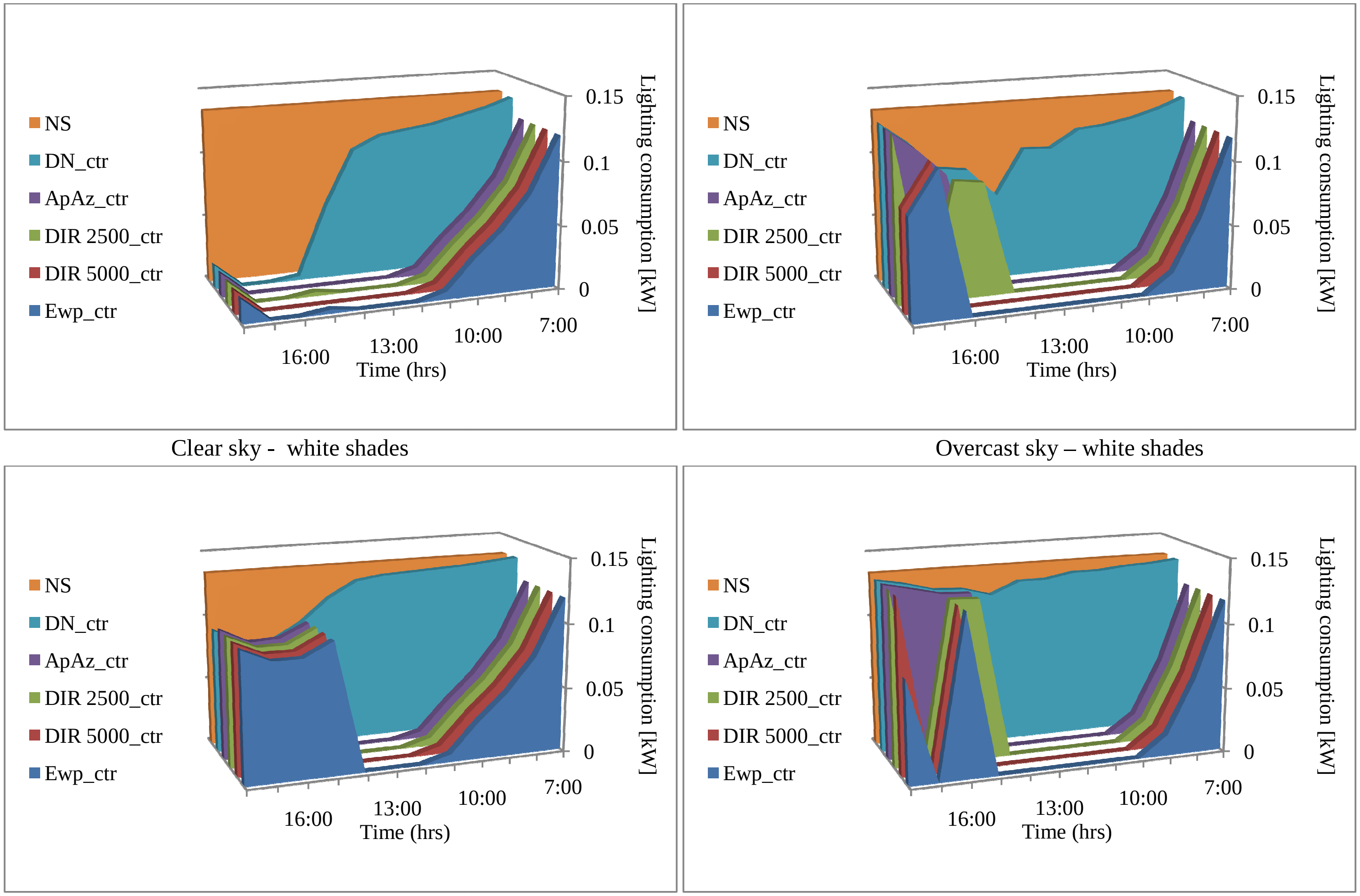
- The base case considers no shade or lighting control, denoted *NS*.
- All-day shade control (*DN_ctr*) is applied with a lighting control system. This strategy assumes the shades to be fully closed at all times and is a worst case scenario where the occupant closes the shade then does not adjust it. These cases are labeled: *WS_DN_ctr* and *DS_DN_ctr*.
- Sunlight penetration shade control is applied with lighting control, considering both a light and dark shade: *WS_ApAz_ctr* and *DS_ApAz_ctr*.
- Direct normal illuminance shade control with lighting control and both shade types, labeled *WS_DIR2500_ctr, WS_DIR5000_ctr, DS_DIR2500_ctr* and *DS_DIR5000_ctr*.
- Work plane illuminance shade control with lighting control: *WS_Ewp_ctr and DS_Ewp_ctr*.

Example data from two cities, heating-dominated Minneapolis and cooling-dominated Phoenix, are shown here for the west and south-facing orientations. The objective of a control strategy is to reduce lighting energy consumption while maintaining acceptable visual quality. Tables **5-5** and **5-6** show the lighting energy required in Minneapolis under each control strategy for the west and south orientation respectively. And tables **5-7** and **5-8** show the same results for Phoenix. The detailed results can be found on appendix **B-1** to **B-8**. Considering the time period from 7am to 7pm DST (12 hrs.), the results in these two cities show significant differences in lighting energy across the different shade and lighting control strategies for a clear day and for an overcast condition.

Automatic shade control strategies (*ApAz_ctr, DIR2500_ctr, DIR5000_ctr and Ewp_ctr*) use less lighting energy than when shades are closed all day with lighting control (*DN_ctr*) for both skies and shade colors [figure **5-3**]. The differences in lighting energy use between automatic shade control strategies are shown on an overcast day only.

For a clear day, lighting consumption is the same for all controls. This means on a clear day, all automatic control strategies perform similarly. Lighting energy reduction is due to more daylight hours that we can leave the shades open during low illuminance situations like overcast skies, which varies across automatic control strategies.

For lighting energy savings, on a clear day, the shades reach similar energy savings under all four automatic control strategies, except for the work plane illuminance control strategy (*DS_Ewp_ctr)* with a dark shade material. On an overcast day, lighting energy varies across the control strategies, as shown in Tables **5-5** to **5-8** in bold. The savings with the dark shades are lower than the savings with the light colored shades.



Clear sky - white shades

Overcast sky – white shades

Clear sky – dark shades

Overcast sky – dark shades

Figure 5-3: Lighting power profile for clear and overcast days in Minneapolis on March 21 and Mar 25 for a **west-facing** private office with occupancy from 7am to 7pm DST.

Table 5-5: The lighting energy savings for clear and overcast days in Minneapolis on March 21 and Mar 25 for a west-facing private office with occupancy from 7am to 7pm DST.

Shade	Sky condition	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
White shade (*WS*)	Clear	44.54%	81.70%	81.50%	81.70%	81.50%
	Overcast	**20.43%**	**67.77%**	**69.26%**	**76.43%**	**77.73%**
Dark shade (*DS*)	Clear	14.90%	59.67%	59.39%	59.39%	59.39%
	Overcast	**5.76%**	**56.81%**	**64.70%**	**72.32%**	**75.67%**

Table 5-6: The lighting energy savings for clear and overcast days in Minneapolis on March 21 and Mar 25 for a south-facing private office with occupancy from 7am to 7pm DST.

Shade	Sky condition	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
White shade (*WS*)	Clear	65.70%	75.31%	75.31%	75.31%	86.43%
	Overcast	**37.22%**	**47.47%**	**51.35%**	**62.81%**	**80.12%**
Dark shade (*DS*)	Clear	19.19%	31.77%	31.77%	31.77%	58.10%
	Overcast	**9.14%**	**20.58%**	**27.82%**	**20.58%**	**65.45%**

Table 5-7: The lighting energy savings for clear and overcast days in Phoenix on March 28 and Mar 20 for a west-facing private office with occupancy from 7am to 7pm DST.

Shade	Sky condition	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
White shade (*WS*)	Clear	42.52%	72.93%	72.93%	72.93%	82.83%
	Overcast	**33.37%**	**60.22%**	**68.54%**	**70.10%**	**86.44%**
Dark shade (*DS*)	Clear	13.13%	50.28%	50.28%	50.28%	64.32%
	Overcast	**8.11%**	**40.92%**	**54.76%**	**62.20%**	**54.76%**

Table 5-8: The lighting energy savings for clear and overcast days in Phoenix on March 28 and Mar 20 for a south-facing private office with occupancy from 7am to 7pm DST.

Shade	Sky condition	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
White shade (*WS*)	Clear	60.11%	71.65%	71.65%	71.65%	79.91%
	Overcast	**34.35%**	**42.51%**	**69.96%**	**73.52%**	**62.69%**
Dark shade (*DS*)	Clear	15.82%	30.75%	30.75%	30.75%	51.72%
	Overcast	**8.26%**	**19.13%**	**70.94%**	**70.68%**	**49.09%**

The results show that by employing these automatic shade control strategies with lighting control, better performance can be achieved, especially on overcast days, which are common in a number of the test cities. The annual lighting energy savings compared to a base case with no shades and no lighting control are presented in figures **5-4** and **5-5** (appendix **B-9** and **B-10**). Results show that these shade control strategies provide lighting energy savings between 40-80% in a west-facing office and 40-78% in the south-facing office for both shade colors when compared to the case without shades. These lighting energy savings represent about 40-70% of total energy savings in each cases.

The always activated shade control (*DN_ctr*) condition presents lighting energy savings of 24-38% for a white shade used on west windows and 29-44% for white shades used on the south windows. Dark shades provide much lower lighting energy savings than white shades on both orientations. The all-day shade used with lighting control presents lighting energy savings of 7-12% when used with dark shades on a west façade and about 8-12% for a dark shade used on a south facade.

Interestingly, with automatic control, for a dark shade, the savings are about 20% lower for a south-facing office compared to a west-facing office, while the savings for a white shade are about the same on both orientations.

The maximum savings occur in the lower latitude, cooling-dominated cities such as Phoenix and Houston with the work plane illuminance automatic control strategy.

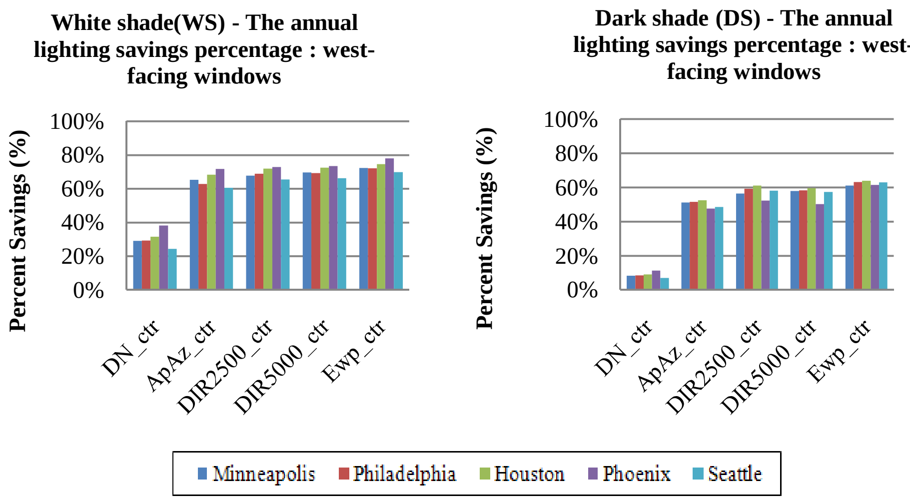


Figure 5-4: The annual lighting savings percentages for west-facing windows under the different control scenarios.

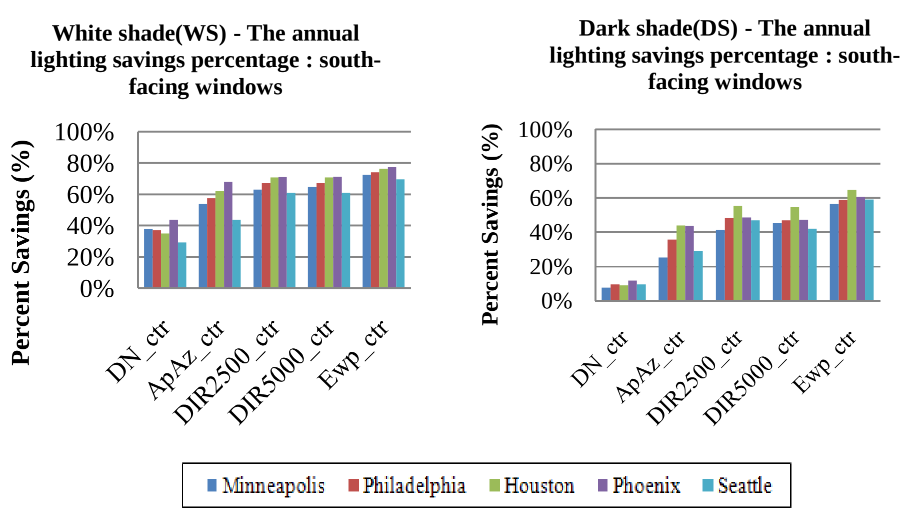


Figure 5-5: The annual lighting savings percentages for south-facing windows under the different control scenarios.

5.2.2 Impact of shades on total, heating, cooling and lighting energy savings with shade closed all day with and without lighting control (*DN, DN_ctr*) and five automatic shade control strategies (*EMWA_ctr, Solxxx_ctr, ApAz_ctr, DIR_ctr, Ewp_ctr)* with automatic lighting control

Tables **5-9** to **5-12** and appendix **B-11** to **B-14** show energy savings in each load category compared to a base case in Minneapolis and Phoenix as representatives of extreme cold and hot climate performance.

The results suggest that work plane illuminance shade control with white shades and lighting control (*WS_Ewp_ctr)* provides maximum total energy savings in both cities in almost all of the cases. The exception occurs on the south windows of Phoenix where the high solar radiation set point control strategy (*Sol630_ctr*) with white shades provides better total energy savings (28.83%). The energy savings received from both shades are 14-15% in Minneapolis and 27-31% in Phoenix.

For heating-dominated Minneapolis, white shades used with automatic control strategies provide better total energy savings than dark shades. Dark shades provide better savings than white shades when used with a all-day closed shade condition with west and south windows.

For a hot climate like Phoenix, using white shades provides more energy savings in all control strategies.

The west-facing orientation works well with the work plane illuminance control strategy for both shade colors. This is due to the higher cooling savings compared with solar radiation set point control. Lighting energy savings are smaller when compared to the solar radiation set point control.

For the south-facing orientation with white shades, the solar radiation control strategy shows higher total energy savings than occurs with the work plane illuminance control strategy. This is because solar radiation control helps to increase the savings for both cooling and lighting energy. Dark shades with work plane illuminance control provides higher savings compared to solar radiation control due to a significant savings in cooling and only a slight decrease in lighting savings.

The visual quality of automatic control strategies are evaluated in the next section.

Table 5-9: Heating, cooling, lighting and total energy savings for an all-day closed shade and automatic shade control strategies in Minneapolis on a west-facing private office with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades.

MN	*DN_WS*	*DN_WS _ctr*	*EMWA_WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ApAz _ctr*	*WS_DIR2500 _ctr*	*WS_DIR5000 _ctr*	*WS_Ewp _ctr*
Heating	-1.93%	-2.98%	-7.35%	-9.37%	-9.03%	-7.46%	-2.70%	-3.69%	-2.86%	-2.54%
Cooling	9.33%	17.15%	19.64%	22.33%	21.93%	14.07%	8.21%	13.43%	8.21%	13.43%
Lighting	0.00%	22.35%	55.56%	64.52%	72.93%	73.03%	65.48%	67.92%	69.73%	71.55%
Total	-0.10%	4.53%	8.29%	9.02%	10.82%	10.87%	11.88%	12.35%	12.58%	13.84%

MN	*DN_DS*	*DN_DS _ctr*	*EMWA_DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ApAz _ctr*	*DS_DIR2500 _ctr*	*DS_DIR5000 _ctr*	*DS_Ewp _ctr*
Heating	1.87%	1.46%	-4.06%	-5.89%	-6.92%	-7.53%	-3.40%	-4.10%	-4.10%	-5.13%
Cooling	-6.25%	-4.64%	3.71%	6.40%	9.72%	14.02%	1.47%	2.25%	2.49%	1.95%
Lighting	0.00%	5.44%	40.69%	51.34%	63.20%	73.00%	51.57%	56.41%	57.01%	61.26%
Total	0.45%	1.44%	5.59%	6.75%	8.77%	10.80%	7.83%	8.40%	8.55%	8.60%

Table 5-10: Heating, cooling, lighting and total energy savings for an all-day closed shade and automatic shade control strategies in Minneapolis on a south-facing private office with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades.

MN	*DN_WS*	*DN_WS _ctr*	*EMWA_WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ApAz _ctr*	*WS_DIR2500 _ctr*	*WS_DIR5000 _ctr*	*WS_Ewp _ctr*
Heating	-6.40%	-9.97%	-11.25%	-17.55%	-16.89%	-7.92%	-6.74%	-6.74%	-0.49%	-4.92%
Cooling	11.55%	19.91%	19.30%	24.67%	24.29%	16.21%	15.59%	15.07%	12.69%	12.93%
Lighting	0.00%	30.98%	35.56%	60.02%	73.50%	73.53%	52.77%	63.09%	61.27%	72.15%
Total	-2.27%	3.53%	3.65%	5.85%	9.16%	13.59%	9.69%	11.87%	15.03%	14.67%

MN	*DN_DS*	*DN_DS _ctr*	*EMWA_DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ApAz _ctr*	*DS_DIR2500 _ctr*	*DS_DIR5000 _ctr*	*DS_Ewp _ctr*
Heating	2.71%	1.77%	1.47%	-4.48%	-6.48%	-8.00%	1.77%	-0.93%	-0.93%	-3.17%
Cooling	-4.37%	-2.57%	-2.19%	5.66%	10.74%	16.11%	2.19%	3.90%	4.61%	6.61%
Lighting	0.00%	7.58%	8.90%	37.57%	56.79%	73.53%	27.95%	41.27%	45.52%	56.43%
Total	1.04%	2.38%	2.54%	6.27%	9.99%	13.52%	7.57%	9.05%	10.09%	11.36%

Table 5-11: Heating, cooling, lighting and total energy savings for an all-day closed shade and automatic shade control strategies in Phoenix on a west-facing private office with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades.

AZ	*DN_WS*	*DN_WS _ctr*	*EMWA_WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ApAz _ctr*	*WS_DIR2500 _ctr*	*WS_DIR5000 _ctr*	*WS_Ewp _ctr*
Heating	-12.35%	-15.20%	-48.22%	-56.29%	-53.68%	-44.89%	-12.59%	-12.59%	-12.59%	-6.41%
Cooling	13.47%	16.00%	10.71%	12.17%	12.19%	10.50%	14.39%	14.39%	14.39%	13.67%
Lighting	0.00%	18.40%	69.34%	69.27%	77.78%	83.28%	72.14%	72.73%	73.36%	78.21%
Total	8.80%	15.47%	24.52%	25.20%	27.63%	28.30%	29.17%	29.33%	29.50%	30.57%

AZ	*DN_DS*	*DN_DS _ctr*	*EMWA_DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ApAz _ctr*	*DS_DIR2500 _ctr*	*DS_DIR5000 _ctr*	*DS_Ewp _ctr*
Heating	-8.55%	-9.03%	-43.47%	-46.56%	-46.56%	-43.23%	-19.71%	-19.71%	-19.71%	-19.71%
Cooling	8.53%	9.16%	-0.03%	0.43%	2.24%	5.03%	12.74%	11.10%	13.01%	12.28%
Lighting	0.00%	4.48%	48.04%	47.61%	59.22%	73.52%	47.91%	52.16%	49.75%	61.26%
Total	5.55%	7.18%	11.47%	11.55%	15.98%	21.94%	21.13%	21.15%	21.81%	24.47%

Table 5-12: Heating, cooling, lighting and total energy savings for an all-day closed shade and automatic shade control strategies in Phoenix on a south-facing private office with window D SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades.

AZ	*DN_WS*	*DN_WS _ctr*	*EMWA_WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ApAz _ctr*	*WS_DIR2500 _ctr*	*WS_DIR5000 _ctr*	*WS_Ewp _ctr*
Heating	-75.86%	-89.08%	-98.28%	-131.61%	-129.31%	-118.39%	-74.14%	-66.09%	-66.09%	-50.00%
Cooling	15.49%	18.30%	10.19%	13.53%	13.43%	10.94%	14.39%	13.43%	14.14%	9.46%
Lighting	0.00%	21.23%	41.66%	59.23%	76.07%	83.95%	71.56%	73.96%	73.96%	79.43%
Total	9.82%	17.41%	17.07%	23.72%	28.27%	28.83%	28.60%	28.70%	29.20%	27.61%

AZ	*DN_DS*	*DN_DS _ctr*	*EMWA_DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ApAz _ctr*	*DS_DIR2500 _ctr*	*DS_DIR5000 _ctr*	*DS_Ewp _ctr*
Heating	-61.49%	-63.22%	-71.84%	-86.21%	-93.10%	-100.00%	-60.92%	-60.92%	-60.92%	-73.56%
Cooling	10.23%	10.94%	-5.20%	-1.24%	2.01%	4.55%	14.88%	15.31%	15.15%	16.53%
Lighting	0.00%	5.17%	10.55%	31.02%	54.22%	72.25%	43.70%	48.55%	47.33%	60.65%
Total	6.31%	8.19%	-1.94%	6.23%	14.76%	21.38%	21.55%	23.18%	22.73%	27.15%

5.2.3 Automatic control strategy comparisons on the building level

The results and analysis of shades closed all day and automatic control strategies for different translucent shades with and without lighting control are presented in figures **5-6** to **5-9** for Minneapolis and Phoenix for west and south-facing windows and both shade colors.

With shades closed all day without lighting control, there is a small potential benefit (about 1%) on total energy savings for a cold climate while it is about 7-12% in a hot climate.

For shades closed all day with lighting control, higher total savings are received from the lighting energy savings for both shade colors with 1-5% in the cold climate and 7-17% in the hot climate.

The automatic control strategies clearly show higher energy savings over the closed shade condition. It is also observed that the white shade outperforms the dark shades in almost all cases except when used with the low and medium solar radiation setpoint control strategies where dark shades performed slightly better on a south orientation in Minneapolis. The savings come from reduced losses in heating energy [table **5-10**, highlighted] which is the majority of energy use in this heating-dominated city.

The time control strategy shows a loss in savings for dark shades on south-facing windows in Phoenix due to increases in cooling energy [table **5-12**]

The maximum savings in Phoenix on the west and south-facing orientations occur with white shades and the high solar radiation control strategy with savings of 28.30% and 28.83%.

The maximum savings in Minneapolis for a west-facing office occur with the work plane illuminance control strategy and white shade with a savings of 13.52%. While on south-facing orientations, the maximum savings of 13.59% occurs with the high solar radiation control strategy with white shades. In the cold climate, the solar radiation control strategies show different performance between the west and the south orientations.

In the hot climate, the solar radiation control strategies provide similar results for west and south orientations while the control set to optimize savings and visual quality provide lower savings on the south-facing offices compared to the west-facing offices due to the restricted sunlight limit and work plane illuminance value. For the solar radiation control strategy, however, there are chances that sunlight can penetrate into the room causing glare concerns and a work plane illuminance level above 2000 lux (200 fc).

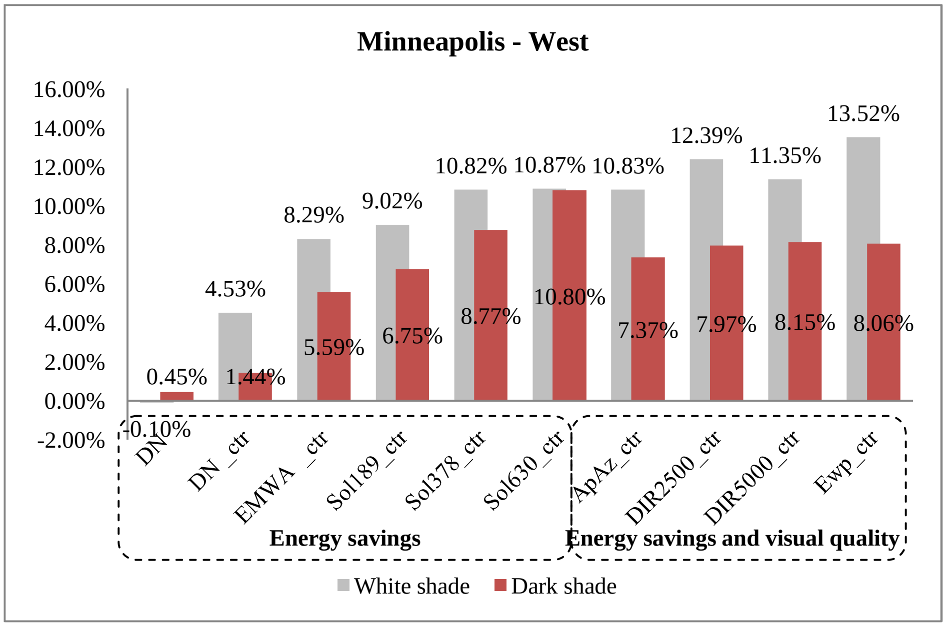


Figure 5-6: The total energy savings comparison for Minneapolis with west-facing windows across different shade control strategies and white and dark shades.

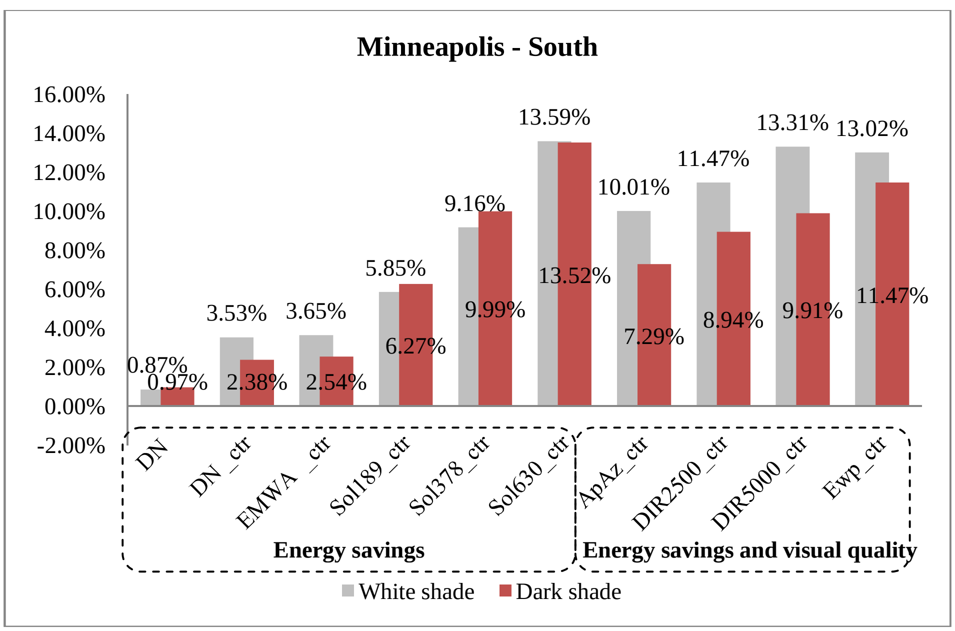


Figure 5-7: The total energy savings comparison for Minneapolis with south-facing windows across different shade control strategies and white and dark shades.

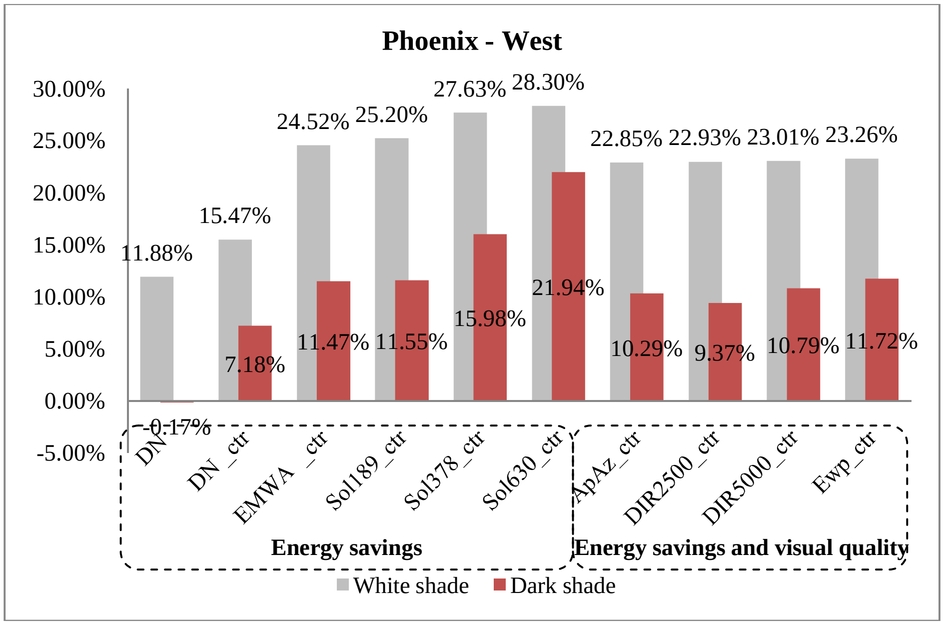


Figure 5-8: The total energy savings comparison for Phoenix with west-facing windows across different shade control strategies and white and dark shades.

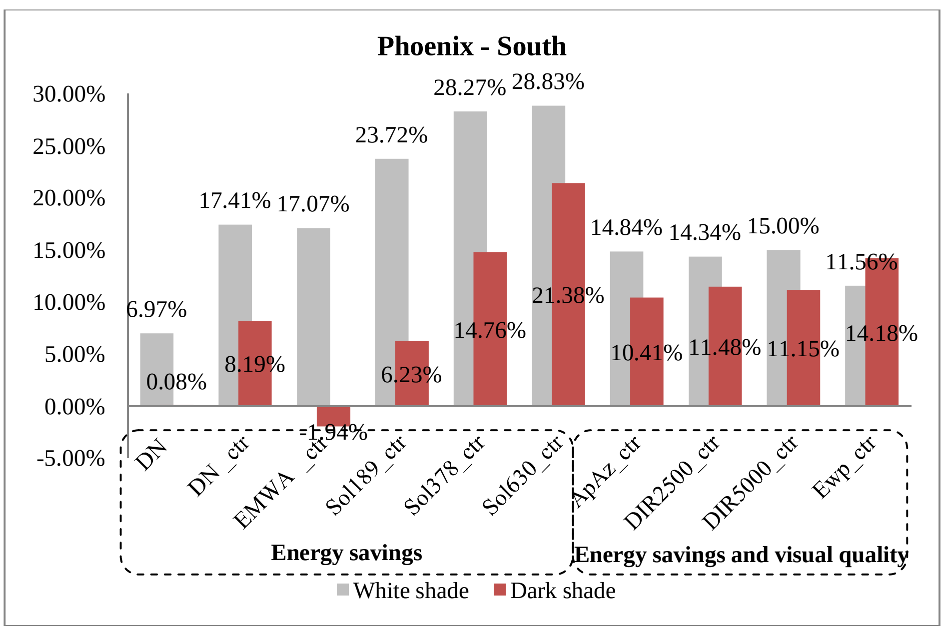


Figure 5-9: The total energy savings comparison for Phoenix with south-facing windows across different shade control strategies and white and dark shades.

5.3 Visual quality analysis

The impact on energy savings of these automatic control strategies was presented in section 5.2, and suggests that the savings are maximized when the shades are deployed the least number of hours with the work plane illuminance control strategy (*Ewp_ctr*) and high solar radiation control strategy (*Sol630_ctr*). However, none of these control strategies guarantee that visual quality will be achieved. This section analyzes visual quality using daylight glare index (DGI), work plane illuminance, luminance ratios and view on studies with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and both shade colors on the west and south-facing windows. The case study selected here is for Minneapolis only, since the evaluation methods are the same and can be applied to other regions.

5.3.1 Work plane illuminance results and analysis

Tables **5-13** to **5-16** and appendix **B-15** to **B-18** show useful daylight illuminance (UDI) which is the number of daylight hours that fall within the beneficial range between 100 and 2000 lux at the critical work plane point for each of the control strategies throughout the year (4,726 daylight hours per year for Minneapolis). The hourly illuminance results at the work plane are obtained from EnergyPlus [Figure **5-2**].

Table 5-13: The useful daylight illuminance (UDI) for **west-facing** offices in Minneapolis with a white shade (*WS*).

	Base case	Static control	Automatic control			
West-facing	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	10.6%	44.7%	18.0%	14.8%	13.6%	11.1%
100<UDI<2000	70.0%	55.3%	**80.4%**	**83.1%**	**84.2%**	**88.6%**
UDI>2000	18.7%	0.0%	1.6%	2.1%	2.3%	0.3%

Table 5-14: The useful daylight illuminance (UDI) for **south-facing** offices in Minneapolis with a white shade (*WS*).

	Base case	Static control	Automatic control			
South-facing	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	12.7%	35.3%	19.3%	16.3%	15.8%	12.7%
100<UDI<2000	59.5%	64.7%	**80.6%**	**81.5%**	**81.7%**	**87.3%**
UDI>2000	27.9%	0.0%	0.2%	2.3%	2.5%	0.0%

For the base case (*NS*), useful daylight levels occur about 70% of the time (3,209 hours out of 4,726 hours) for the west-facing space and 59.5% (2,811 hours out of 4,726 hours) for the south-facing space. However, the hours that UDI exceeds 2000 lux are about 22 and 28% for west and south-facing offices. With a static shade control, all hours are less than 2000 lux, although only about 55-65% of the hours achieve 'useful' daylight. When automatic shade controls are applied, the daylight illuminance achieves useful levels of illuminance 80-88% of the time with the white shade (Tvis=0.14).

The dark shade with static control significantly reduces the times with useful daylight to about 17 and 21.7% respectively for west and south-facing windows. The automatic control strategies, however, still show better performance, especially with work plane illuminance control, with UDI reaching up to 82.1% on west-facing windows and 79.2% on south-facing windows. The rest of the automatic control strategies perform as expected due to the lower transmittance of the dark shade (Tvis=0.04).

Table 5-15: The useful daylight illuminance (UDI) for west-facing offices in Minneapolis with a dark shade (*DS*).

	Base case	Static control	Automatic control			
West-facing	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	10.6%	83.1%	32.3%	25.3%	23.8%	17.6%
100<UDI<2000	70.0%	16.9%	**66.0%**	**72.6%**	**74.0%**	**82.1%**
UDI>2000	18.7%	0.0%	1.8%	2.1%	2.3%	0.3%

Table 5-16: The useful daylight illuminance (UDI) for south-facing offices in Minneapolis with a dark shade (*DS*).

	Base case	Static control	Automatic control			
South-facing	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	12.7%	78.3%	51.9%	37.4%	38.1%	20.8%
100<UDI<2000	59.5%	21.7%	**48.1%**	**62.7%**	**61.9%**	**79.2%**
UDI>2000	27.9%	0.0%	0.0%	0.0%	0.0%	0.0%

5.3.2 Daylight glare index (DGI) results and analysis

The daylight glare index data in this study assumes a worst case scenario in which the occupants sit and view the window directly [figure **5-10**] which does not represent good office planning. The threshold of a "just comfortable" condition is 22, so values greater than 22 are considered to be objectionable.

DGI values presented in tables **5-17** to **5-20** and appendix **B-19** to **B-22** for a west and south-facing office in Minneapolis show that static control, as expected, provides conditions within the comfort range of DGI 92.4% of the time.

For automatic control strategies, DGI values are below 22 only 66-73% and 66-70% of the time for white and dark shades respectively. The DGI values suggest similar results for the south-orientation. If an automatic control strategy is to be selected based on DGI, sun penetration control (*ApAz_ctr*) is the best of those tested, but only by a small margin.

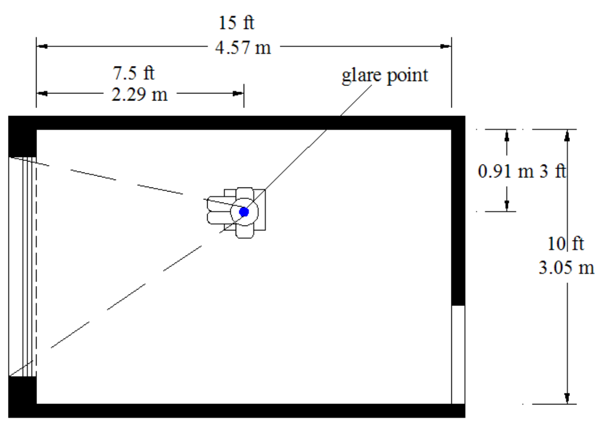


Fig 5-10: Glare measurement point with the occupant sitting and viewing the window directly.

Table 5-17: The Daylight Glare Index (DGI) for west-facing offices in Minneapolis with a white shade (*WS*).

	Base case	Static control	Automatic control			
West-facing	*NS*	*DN_WS*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	47.1%	92.4%	73.0%	68.8%	67.2%	65.8%
22<DGI≤24	20.5%	0.2%	15.3%	16.4%	16.6%	19.1%
DGI>24	32.3%	0.0%	11.7%	14.9%	16.0%	15.0%

Table 5-18: The Daylight Glare Index (DGI) for south-facing offices in Minneapolis with a white shade (*WS*).

	Base case	Static control	Automatic control			
South-facing	*NS*	*DN_DS*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	44.0%	90.1%	86.4%	75.0%	74.4%	67.2%
22<DGI≤24	17.2%	2.3%	8.7%	10.6%	10.7%	16.1%
DGI>24	38.8%	0.0%	4.9%	14.4%	14.9%	16.7%

Table 5-19: The Daylight Glare Index (DGI) for west-facing offices in Minneapolis with a dark shade (*DS*).

	Base case	Static control	Automatic control			
West-facing	*NS*	*DN_WS*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	47.1%	65.7%	69.8%	66.3%	65.5%	66.0%
22<DGI≤24	20.5%	0.0%	14.9%	16.2%	16.4%	19.0%
DGI>24	32.3%	0.0%	15.3%	17.5%	18.1%	15.0%

Table 5-20: The Daylight Glare Index (DGI) for south-facing offices in Minneapolis with a dark shade (*DS*).

	Base case	Static control	Automatic control			
South-facing	*NS*	*DN_DS*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	44.0%	73.8%	86.2%	74.0%	70.3%	69.5%
22<DGI≤24	17.2%	0.0%	6.0%	8.3%	9.9%	13.8%
DGI>24	38.8%	0.0%	7.9%	17.7%	19.8%	16.7%

5.3.3 Luminance ratio results and analysis

To further analyze visual quality in the presence of shades, two lighting simulation programs, AGI32 and DAYSIM were used to model a space with window D, as well as with both white and dark shades (which are assumed to be Lambertian) to obtain luminance ratios for specific locations within the room. The difference between these two programs is that AGI32 applies the CIE sky conditions with the radiosity method while DAYSIM uses the Perez all weather skies with a daylight coefficient approach. The IESNA (IESNA 2000) states that luminance ratios generally should not exceed the following recommended ratios for critical work tasks:

Between paper task and adjacent VDT screen	3:1 or	1:3
Between task and adjacent surroundings	3:1 or	1:3
Between task and remote (nonadjacent) surfaces	10:1 or	1:10

Test room surface reflectances and transmittance:

Ceiling reflectance	0.80	White shade transmittance	0.14
Wall reflectance	0.60	White shade reflectance	0.71
Floor reflectance	0.30	Dark shade transmittance	0.04
Window transmittance	0.64	Dark shade reflectance	0.05

Sensor locations (Figure **5-11**)

Task

- Video Display Terminal (VDT) represents a self-luminous vertical task
- Paper (PAPER) represents a horizontal task

Adjacent surroundings

- Adjacent wall (ADJ), the wall behind the VDT

Remote surfaces

- Remote wall (REMOTE), the wall behind the VDT but at a point near the window
- Window (WINDOW), window surfaces with or without shades

AGI32 analysis: Luminance ratios of clear and overcast skies

The AGI32 analysis was done with two types of sky: a clear sky and an overcast sky. The date selected for simulation was Mar 21st at 4pm on a west-facing window. However, this condition may not increase the wall luminance much due to the high angle of the sun. The model and location of the luminance ratio measurement points are shown in figure **5-11**. The model is simulated with the use of daylighting only to see the impact of shade use in a situation where there is no electric light in the room.

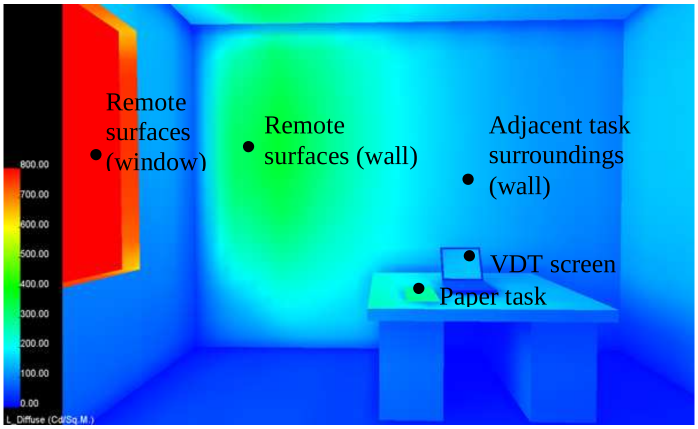


Fig 5-11: Measurement points for the luminance ratio analysis from AGI32.

The luminous exitances and luminances obtained from AGI32 simulations are listed in tables **5-21** and **5-22** for Minneapolis, for west and south- facing windows with both shade colors. Two primary tasks were analyzed, a paper task (PAPER) and a Video Display Terminal unit (VDT). For the VDT, an average luminance of 200 cd/m^2 is applied for the self-luminous monitor. Bolded values represent the values exceeding the recommended ratios. Table **5-23** and **5-24** show the luminance ratios for the comparison between proximate and distant surfaces. For the window, the luminance ratios are high, but if the occupant faces parallel to the window wall, the window may not be in the occupants' general field of view

Clear sky

When shades are not in use under clear sky conditions, there is a chance for the luminance ratios between the VDT or PAPER and the remote wall surface (REMOTE) to exceed the recommended value. This is due to the high transmittance of the glazing itself (Tvis=0.64).

When shades are used, the results are acceptable except for a slightly high value for dark shades between VDT, paper, adjacent surfaces (ADJ), and remote surface (REMOTE). This is due to the high screen luminance (202.5 cd/m^2) and the darker surroundings of the room (from 2.9-47.6 cd/m^2) resulting from low shade reflectance (ρ=0.05) and transmittance (Tvis=0.04), but the addition of electric lighting should reduce this ratio. The dark shades also produce a good result for the paper task especially for overcast skies but not for the VDT task.

Overcast sky

For an overcast sky, the no shade case seems to work well. A problem occurs when shades are used due to the high luminance of the VDT screen as seen in table **5-24.** It is shown that other room surface luminance values change when compared to the no shade base case (*NS*) but the VDT screen luminance still remains at 200 cd/m^2.

Table 5-21: Luminous exitance values (lumen/m^2) from measurement points for luminance ratio analysis.

Exitance (lux)				VDT	PAPER	REMOTE	WINDOW	ADJ
No shade (*NS*)								
west	21-Mar	4pm	overcast	245.3	338.9	326.0	95.8	585.3
		4pm	clear	1657.0	**2399.5**	**3045.1**	1366.5	**35959.9**
White shade (*WS*)								
west	21-Mar	4pm	overcast	50.6	72.1	75.3	46.3	122.7
		4pm	clear	723.1	1007.1	1071.7	651.0	1732.4
Dark shade (*DS*)								
west	21-Mar	4pm	overcast	10.8	15.1	15.1	12.9	24.7
		4pm	clear	194.8	203.4	288.4	175.4	350.8

Note: values above 2000 lux are highlight in bold

Table 5-22: Luminance values (cd/m^2) from measurement points for luminance analysis.

Luminance (cd/m^2)				VDT	PAPER	REMOTE	ADJ	WINDOW
No shade (*NS*)								
west	21-Mar	4pm	overcast	203.9	97.1	62.3	111.8	401.7
		4pm	clear	226.4	687.4	581.6	6867.8	9501.0
White shade (*WS*)								
west	21-Mar	4pm	overcast	200.8	20.7	14.4	23.4	242.3
		4pm	clear	211.5	288.5	204.7	330.9	3412.3
Dark shade (*DS*)								
west	21-Mar	4pm	overcast	200.2	4.3	2.9	4.7	47.6
		4pm	clear	203.1	58.3	55.1	67.0	670.1

Table 5-23: Luminance ratios for Minneapolis, west-facing window on Mar 21st, at 4pm and clear sky (VDT screen at 200 cd/m2).

Clear sky	VDT : PAPER	PAPER: ADJ	VDT: ADJ	PAPER: REMOTE	VDT: REMOTE	PAPER: WINDOW	VDT: WINDOW
No shade	3.0 : 1	1.2 : 1	2.6 : 1	**1 : 10**	**1 : 12**	**1 : 14**	**1 : 16.4**
White shade	1.4 : 1	1.4 : 1	1 : 1	1 : 1.1	1.1 : 1	**1 : 12**	1 : 9.3
Dark shade	**3.5 : 1**	1.1 : 1	**1.2 : 1**	1 : 1.1	3.7 : 1	**1 : 11.5**	1 : 2.7

Table 5-24: Luminance ratios for Minneapolis, west-facing window on Mar 21st, at 4pm and overcast sky (VDT screen at 200 cd/m2).

Overcast sky	VDT : PAPER	PAPER: ADJ	VDT: ADJ	PAPER: REMOTE	VDT: REMOTE	PAPER: WINDOW	VDT: WINDOW
No shade	2.1 : 1	1.6 : 1	1 : 1.2	1 : 1.2	1.8 : 1	1: 4.1	1: 2.0
White shade	**9.7 : 1**	1.4 : 1	**14.0 : 1**	1 : 1.1	8.6 : 1	**1 : 11.7**	1 : 1.1
Dark shade	**47 : 1**	1.5 : 1	**70.0 : 1**	1 : 1.1	**42.4 : 1**	**1 : 11**	4.2 : 1

DAYSIM: Annual luminance ratios simulation

DAYSIM provides detailed results of illuminance and luminance values for the whole year. Simulation cases were performed for two different cities, Minneapolis and

Phoenix, with two shade colors. The window used in the simulations is window D (SHGC=0.28/ U=1.61/ Tvis=0.64) with WWR 0.40. Annual hourly illuminances are computed at the measurement points used for AGI32 [Figure **5-11**]. The average window luminance is obtained using a shield illuminance sensor as shown in figure **5-12**. The illuminance values are simulated and used to calculate the luminance ratios.

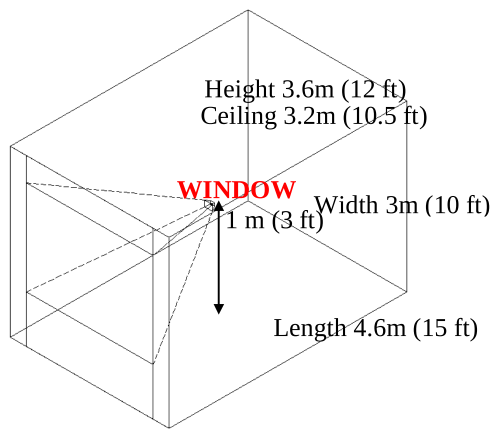


Fig 5-12: A shielded illuminance sensor's location.

Luminance ratio analysis

The goal of this analysis is to study the impact of shade use and the impact of automatic control of shades on luminance ratios.Luminance ratios throughout the year are addressed by calculating the number of daylight hours that luminance ratios at the points of interest exceed the recommended value. The luminance ratios are reported as two task-to-background ratios. **The low:high ratio** is the ratio on the low side of the comparison pair such as 1:3 for close proximity surfaces 1:10 for distant surfaces. And **the high:low ratio** considers the task on the high side of that comparison, 3:1 and 10:1 for close proximity and distance surfaces. The higher the number of hours, the higher the possibility that luminance will be an issue negatively impacting an occupant's visual quality.

Luminance ratio comparison between the base case (*NS*) and a case with shades used at all times (*DN*) without electric lights

The results showing the impact of white and dark shades compared to the base case in two different cities and orientations are shown in figures **5-14** to **5-17**.

The results show that in both cities and orientations, the case without shades (*NS*) provides conditions that go above and beyond the recommended values throughout the year in all comparison pairs. The values exceed the recommended values in both the high:low ratio (3:1 and 10:1) and the low:high ratio (1:3 and 1:10) cases with a greater number on the low side. This means the condition without shades changes dramatically throughout the year.

For cases with shades (*DN*), both cities and both orientations show similar trends where only VDT:ADJ, VDT:WINDOW and PAPER:WINDOW, exceed the recommended values.

For VDT:ADJ, the exceeded hours result from the high:low ratio which means the VDT is brighter than the adjacent wall behind it. Further analysis shows that those hours represent the near nighttime condition in which the VDT screen luminance value is already brighter than the wall luminance [table **5-25**], hence, the high number of hours in this comparison.

For VDT:WINDOW and PAPER:WINDOW, these ratios occur because of the bright window. With white shades there is a possibility that the window is too bright for the occupants for both the paper task and the VDT task.

The following figure, figure **5-13**, shows the differences between the luminance ratios (the high ratio) for the VDT: ADJ case. By allowing daylight into the room, the luminance ratios are reduced from the night time condition at 3.81:1 to 1.8:1 and 3:1 for the white shade and dark shade at 3PM. The case without shades helps improve the luminance ratios. This condition admits too much daylight, causing the adjacent wall to get too bright and exceeds the low:high ratios (1:5). Without shades, glare conditions can occur.

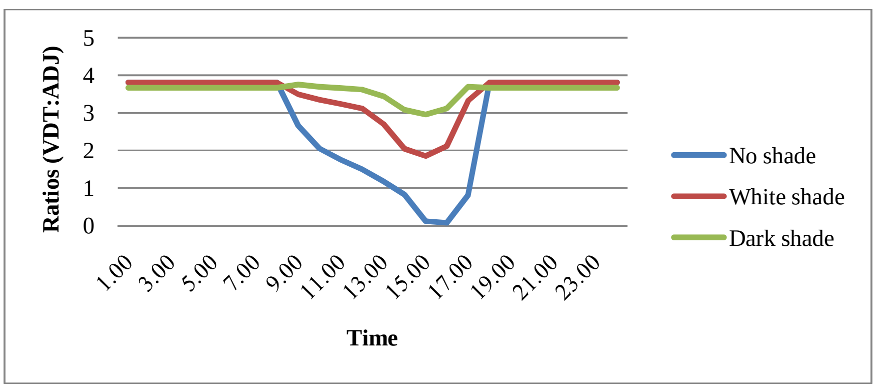
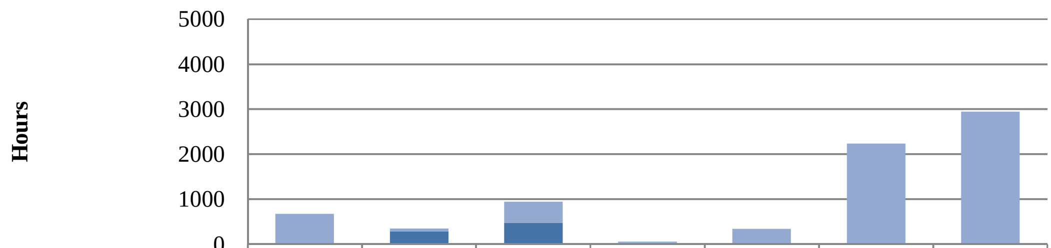


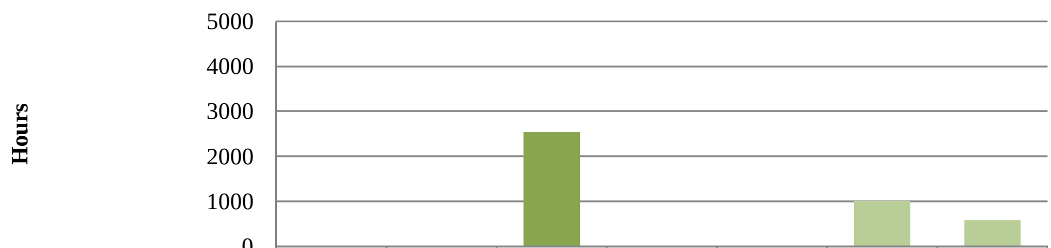
Fig 5-13: The luminance ratio comparison between the VDT screen and the adjacent wall (ADJ) on a single day.

Table 5-25: Luminance ratios of the night time condition with only electric lights.

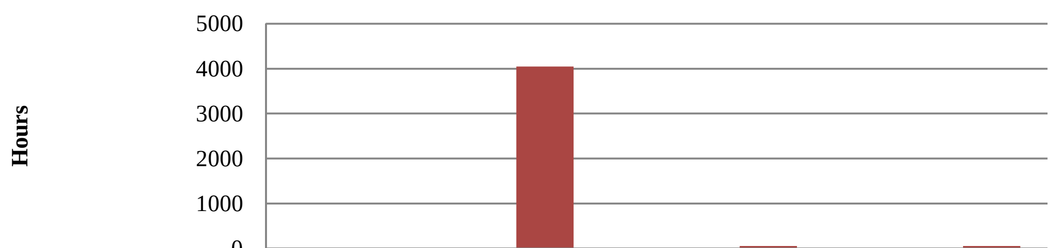
Shade condition	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT : ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT: REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT: WINDOW (1:10 or 10:1)
	<=0.33 or >=3	<=0.33 or >=3	<=0.33 or >=3	<=0.1 or >=10	<=0.1 or >=10	<=0.1 or >=10	<=0.1 or >=10
NS	1.48 : 1	2.57: 1	3.81:1	4.80:1	7.12:1	6.52:1	9.66:1
WS	1.48 : 1	2.57: 1	3.81:1	4.77:1	7.08:1	6.49:1	9.62:1
DS	1.45 : 1	2.53: 1	3.67:1	4.36:1	6.35:1	6.25:1	9.09:1



	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER:REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
No shade (low ratio)	677	73	469	30	337	2238	2946
No shade (high ratio)	0	282	476	27	0	0	0

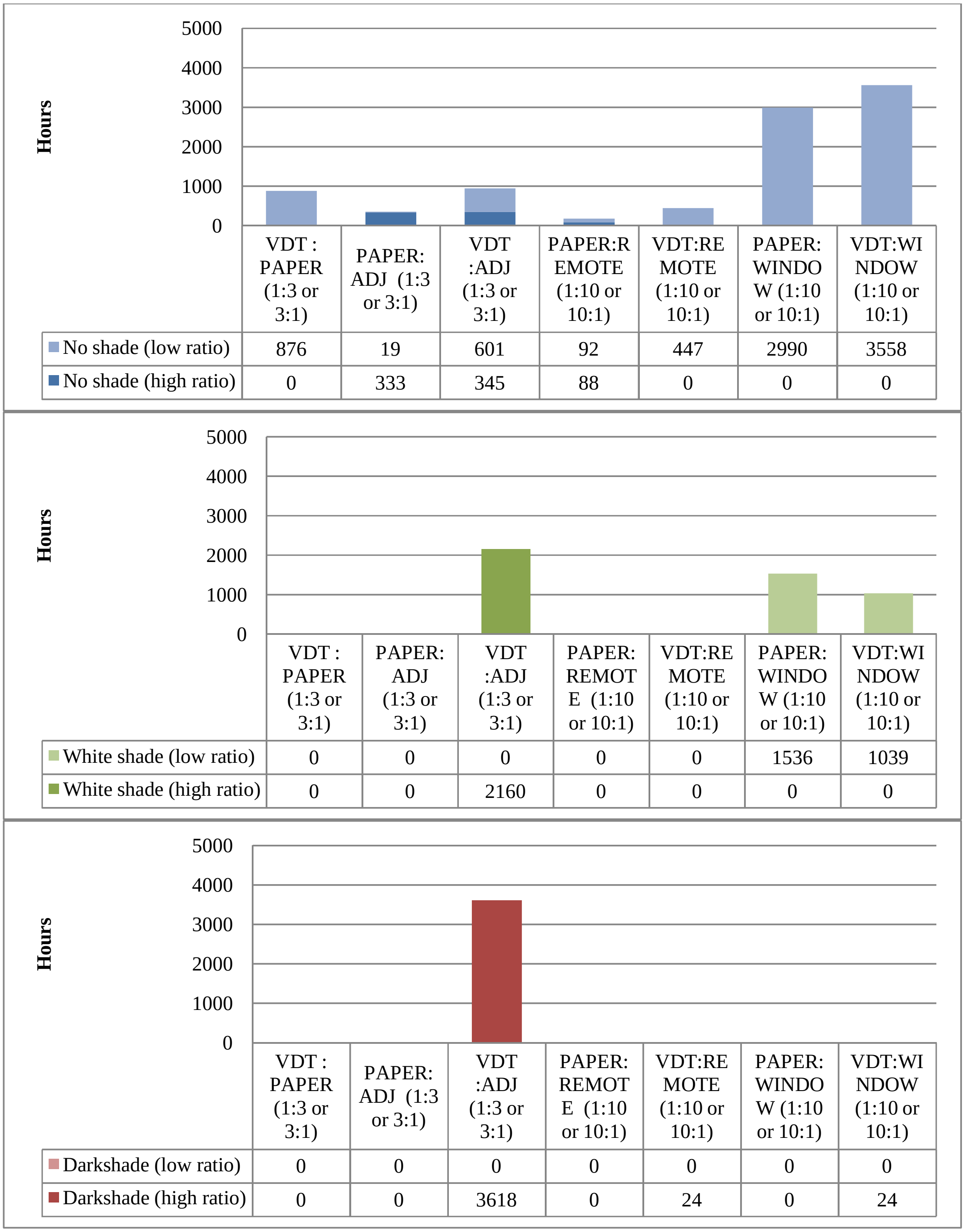


	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
White shade (low ratio)	0	0	0	0	0	1010	580
White shade (high ratio)	0	0	2535	0	0	0	0



	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
Dark shade (low ratio)	0	0	0	0	0	0	0
Dark shade (high ratio)	0	0	4042	0	60	0	60

Fig 5-14: The number of hours that exceed recommended values for luminance ratios, west-facing window in Minneapolis with window D and WWR 0.40 (1:3 and 3:1 for close proximity surfaces and 1:10 and 10:1 for distant surfaces).

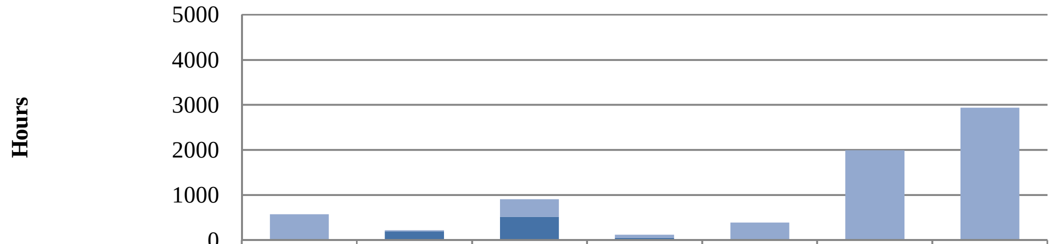


	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER:REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
No shade (low ratio)	876	19	601	92	447	2990	3558
No shade (high ratio)	0	333	345	88	0	0	0

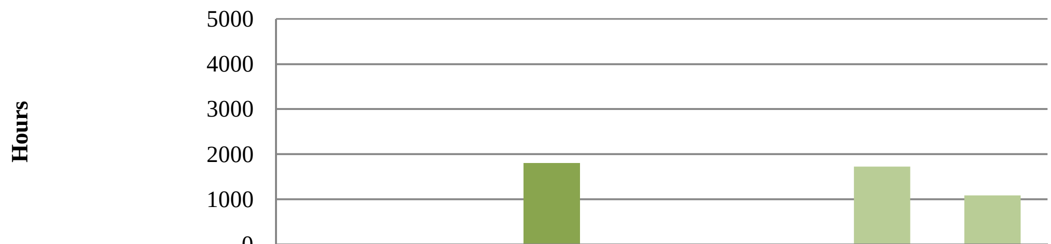
	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
White shade (low ratio)	0	0	0	0	0	1536	1039
White shade (high ratio)	0	0	2160	0	0	0	0

	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
Darkshade (low ratio)	0	0	0	0	0	0	0
Darkshade (high ratio)	0	0	3618	0	24	0	24

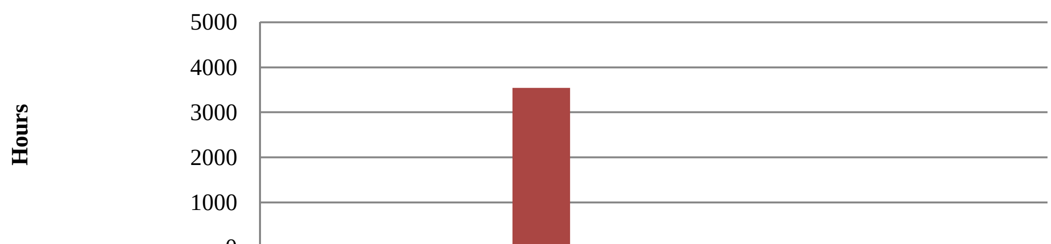
Fig 5-15: The number of hours that exceed recommended values for luminance ratios, west-facing window in Phoenix with window D and WWR 0.40 (1:3 and 3:1 for close proximity surfaces and 1:10 and 10:1 for distant surfaces).



	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER:REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
Noshade (high ratio)	571	27	393	75	394	1996	2931
Noshade (low ratio)	0	194	519	47	0	0	0

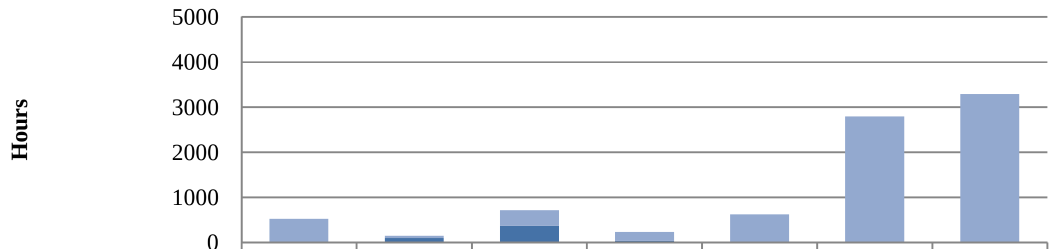


	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
White shade (low ratio)	0	0	0	0	0	1726	1086
White shade (high ratio)	0	0	1799	0	0	0	0

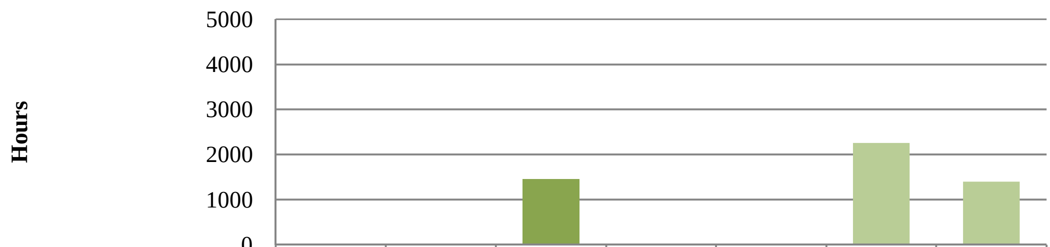


	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
Darkshade (low ratio)	0	0	0	0	0	26	0
Darkshade (high ratio)	0	0	3542	0	59	0	59

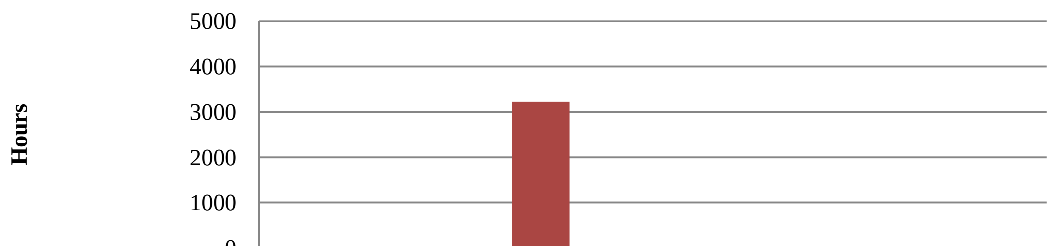
Fig 5-16: The number of hours that exceed recommended values for luminance ratios, south-facing window in Minneapolis with window D and WWR 0.40 (1:3 and 3:1 for close proximity surfaces and 1:10 and 10:1 for distant surfaces).



	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER:REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
Noshade (high ratio)	527	47	340	195	629	2794	3296
Noshade (low ratio)	0	103	375	37	0	0	0



	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
White shade (low ratio)	0	0	0	0	0	2261	1403
White shade (high ratio)	0	0	1459	0	0	0	0



	VDT : PAPER (1:3 or 3:1)	PAPER: ADJ (1:3 or 3:1)	VDT :ADJ (1:3 or 3:1)	PAPER: REMOTE (1:10 or 10:1)	VDT:REMOTE (1:10 or 10:1)	PAPER: WINDOW (1:10 or 10:1)	VDT:WINDOW (1:10 or 10:1)
Darkshade (low ratio)	0	0	0	0	0	33	0
Darkshade (high ratio)	0	0	3229	0	27	0	27

Fig 5-17: The number of hours that exceed recommended values for luminance ratios, south-facing window in Phoenix with window D and WWR 0.40 (1:3 and 3:1 for close proximity surfaces and 1:10 and 10:1 for distant surfaces).

Luminance ratio comparison between a base case (*NS*) and automatic shade control strategies with electric lights

Luminance ratio comparisons were made between control strategies with the use of electric lights [Table **5-26** to **5-29**]. The results show the number of hours that luminance ratios exceed the recommended values.

Hi: Lo means the task surface comparison is higher than the room surface and vice versa. For example, NS – Hi:Lo shows PAPER:ADJ equal to 282 which means there are 282 hours a year that the PAPER task has a higher luminance than the adjacent wall (ADJ) and exceed the ratio of 3:1.

The results show that the use of automatic shade control strategies helps improve the luminance ratios in most of the cases compared to the no shade base case (*NS*) which has excessive luminance ratios appearing in all comparisons. The use of shades in some cases can result in zero hours of high values in many ratio comparisons.

For the task to task and proximate surface luminance ratios, the work plane illuminance control strategy provides the least number of hours with excessive values for both white and dark shades.

For the task to distant surface luminance ratios, white and dark shade all day control (*DN*) shows the least hours. When comparing only across automatic control strategies, the work plane illuminance control strategy shows an acceptable number of high ratio hours for the ratio of task luminance to the wall behind the table. The exception occurs on the PAPER: WINDOW and VDT:WINDOW cases where the work plane illuminance control strategy shows the greatest number of hours with high ratios compared to the other automatic control strategies. This is due to the high luminance of the window itself without shades that creates a ratio greater than 1:10 (Lo: Hi). This type of control strategy has the highest number of no shade hours so the number of hours with excessive luminance ratios is high. However, the luminance ratios for the window may not generally be in the occupants' general field of view if the worker faces parallel to the window wall.

For luminance ratios, the south orientation shows a higher number of hours exceeding the recommended value compared to the west orientation.

White shades and dark shades show similar performance for the proximate surface. For the distant surfaces, especially with the WINDOW, dark shades perform better than white shades due to their lower transmittance.

A significant number of hours with high luminance ratios occurs with these three ratios: VDT:ADJ for task to proximate surface, PAPER:WINDOW and VDT:WINDOW for task to distance surface. The VDT:ADJ values are shown in table **5-25** where the room itself has the issue of excessive luminance ratios at the nighttime condition already. Here, the use of shades and shade control strategies help reduce the high ratio hours. And for the WINDOW, more human subject studies on visual quality and user preference should be done to provide information on visual quality of distant surfaces which are not in the field of view, like the window in this case.

Table 5-26: The number of hours that exceed recommended values for luminance ratios, west-facing window in Minneapolis with window D and WWR=0.40 (1:3 and 3:1 are uses for close proximate surfaces and 1:10 and 10:1 for more distant surfaces).

	Proximate surfaces (1:3 or 3:1)			Distant surface (1:10 or 10:1)			
Control Strategy	VDT : PAPER	PAPER: ADJ	VDT : ADJ	PAPER: REMOTE	VDT: REMOTE	PAPER: WINDOW	VDT: WINDOW
NS-Hi:Lo	0	282	476	27	0	0	0
NS-Lo:Hi	677	73	469	30	337	2238	2946
WS-Hi:Lo	0	0	2535	0	0	0	0
WS-Lo:Hi	0	0	0	0	0	1010	580
WS_ApAz-Hi:Lo	0	2	316	0	0	0	0
WS_ApAz-Lo:Hi	68	1	182	0	66	2550	2286
WS_DIR2500-Hi:Lo	0	9	294	0	0	0	0
WS_DIR2500-Lo:Hi	84	1	182	0	68	2561	2395
WS_DIR5000-Hi:Lo	0	10	283	0	0	0	0
WS_DIR5000-Lo:Hi	88	1	182	0	68	2577	2420
WS_Ewp-Hi:Lo	0	0	217	0	0	0	0
WS_Ewp-Lo:Hi	0	25	266	6	93	2819	2693
DS-Hi:Lo	0	0	4042	0	60	0	60
DS-Lo:Hi	0	0	0	0	0	0	0
DS_ApAz-Hi:Lo	0	2	1371	0	16	0	16
DS_ApAz-Lo:Hi	68	1	10	0	66	1865	1841
DS_DIR2500-Hi:Lo	0	9	492	11	16	0	16
DS_DIR2500-Lo:Hi	84	1	182	0	68	1889	1956
DS_DIR5000-Hi:Lo	0	10	463	9	13	0	13
DS_DIR5000-Lo:Hi	88	1	182	0	68	1906	1981
DS_Ewp-Hi:Lo	0	0	217	0	0	0	0
DS_Ewp-Lo:Hi	0	25	266	6	93	2161	2223

Table 5-27: The number of hours that exceed recommended values for luminance ratios, west-facing window in Phoenix with window D and WWR=0.40 (1:3 and 3:1 are uses for close proximate surfaces and 1:10 and 10:1 for more distant surfaces).

	Proximate surfaces (1:3 or 3:1)			Distant surface (1:10 or 10:1)			
Control Strategy	VDT : PAPER	PAPER: ADJ	VDT : ADJ	PAPER: REMOTE	VDT: REMOTE	PAPER: WINDOW	VDT: WINDOW
NS-Hi:Lo	0	333	345	88	0	0	0
NS-Lo:Hi	876	19	601	92	447	2990	3558
WS-Hi:Lo	0	0	2160	0	0	0	0
WS-Lo:Hi	0	0	0	0	0	1536	1039
WS_ApAz-Hi:Lo	0	0	194	0	0	0	0
WS_ApAz-Lo:Hi	71	0	50	28	67	3444	3052
WS_DIR2500-Hi:Lo	0	60	811	12	3	0	3
WS_DIR2500-Lo:Hi	221	0	163	32	143	2482	2457
WS_DIR5000-Hi:Lo	0	64	474	12	0	0	0
WS_DIR5000-Lo:Hi	236	2	180	34	154	3347	3170
WS_Ewp-Hi:Lo	0	0	134	0	0	0	0
WS_Ewp-Lo:Hi	0	0	245	0	168	3598	3349
DS-Hi:Lo	0	0	3618	0	24	0	24
DS-Lo:Hi	0	0	0	0	0	0	0
DS_ApAz-Hi:Lo	0	0	915	0	3	0	3
DS_ApAz-Lo:Hi	71	0	58	7	67	2378	2202
DS_DIR2500-Hi:Lo	0	60	811	12	3	0	3
DS_DIR2500-Lo:Hi	221	0	163	32	143	2482	2457
DS_DIR5000-Hi:Lo	0	64	780	12	2	0	2
DS_DIR5000-Lo:Hi	236	2	180	34	154	2513	2495
DS_Ewp-Hi:Lo	0	0	134	0	0	0	0
DS_Ewp-Lo:Hi	0	0	245	0	168	2761	2636

Table 5-28: The number of hours that exceed recommended values for luminance ratios, south-facing window in Minneapolis with window D and WWR=0.40 (1:3 and 3:1 are uses for close proximate surfaces and 1:10 and 10:1 for more distant surfaces).

	Proximate surfaces (1:3 or 3:1)			Distant surface (1:10 or 10:1)			
Control Strategy	VDT : PAPER	PAPER: ADJ	VDT : ADJ	PAPER: REMOTE	VDT: REMOTE	PAPER: WINDOW	VDT: WINDOW
NS-Hi:Lo	0	194	519	47	0	0	0
NS-Lo:Hi	571	27	393	75	394	1996	2931
WS-Hi:Lo	0	0	1799	0	0	0	0
WS-Lo:Hi	0	0	0	0	0	1726	1086
WS_ApAz-Hi:Lo	0	0	280	0	0	0	0
WS_ApAz-Lo:Hi	0	0	78	0	7	2354	1581
WS_DIR2500-Hi:Lo	0	2	287	0	0	0	0
WS_DIR2500-Lo:Hi	22	0	96	0	15	2507	2073
WS_DIR5000-Hi:Lo	0	3	287	0	0	0	0
WS_DIR5000-Lo:Hi	35	0	106	0	15	2513	2100
WS_Ewp-Hi:Lo	0	0	202	0	0	0	0
WS_Ewp-Lo:Hi	0	0	386	0	173	2538	2763
DS-Hi:Lo	0	0	3542	0	59	0	59
DS-Lo:Hi	0	0	0	0	0	26	0
DS_ApAz-Hi:Lo	0	0	719	8	8	0	8
DS_ApAz-Lo:Hi	0	0	78	0	7	720	495
DS_DIR2500-Hi:Lo	0	2	459	11	14	0	14
DS_DIR2500-Lo:Hi	22	0	96	0	15	937	997
DS_DIR5000-Hi:Lo	0	3	438	11	14	0	14
DS_DIR5000-Lo:Hi	35	0	106	0	15	948	1026
DS_Ewp-Hi:Lo	0	0	202	0	0	0	0
DS_Ewp-Lo:Hi	0	0	386	0	173	1990	2304

Table 5-29: The number of hours that exceed recommended values for luminance ratios, south-facing window in Phoenix with window D and WWR=0.40 (1:3 and 3:1 are uses for close proximate surfaces and 1:10 and 10:1 for more distant surfaces).

	Proximate surfaces (1:3 or 3:1)			Distant surface (1:10 or 10:1)			
Control Strategy	VDT : PAPER	PAPER: ADJ	VDT : ADJ	PAPER: REMOTE	VDT: REMOTE	PAPER: WINDOW	VDT: WINDOW
NS-Hi:Lo	0	103	375	37	0	0	0
NS-Lo:Hi	527	47	340	195	629	2794	3296
WS-Hi:Lo	0	0	1459	0	0	0	0
WS-Lo:Hi	0	0	0	0	0	2261	1403
WS_ApAz-Hi:Lo	0	0	166	0	0	0	0
WS_ApAz-Lo:Hi	0	0	56	0	12	3151	1961
WS_DIR2500-Hi:Lo	0	28	227	0	0	0	0
WS_DIR2500-Lo:Hi	148	19	200	64	175	3084	2269
WS_DIR5000-Hi:Lo	0	30	228	0	0	0	0
WS_DIR5000-Lo:Hi	161	20	216	70	191	3067	2288
WS_Ewp-Hi:Lo	0	0	132	0	0	0	0
WS_Ewp-Lo:Hi	0	0	537	0	354	3322	3228
DS-Hi:Lo	0	0	3229	0	27	0	27
DS-Lo:Hi	0	0	0	0	0	33	0
DS_ApAz-Hi:Lo	0	0	335	2	2	0	2
DS_ApAz-Lo:Hi	0	0	56	0	12	938	559
DS_DIR2500-Hi:Lo	0	28	368	5	5	0	5
DS_DIR2500-Lo:Hi	148	19	200	64	175	1365	1220
DS_DIR5000-Hi:Lo	0	30	359	5	5	0	5
DS_DIR5000-Lo:Hi	161	20	216	70	191	1385	1262
DS_Ewp-Hi:Lo	0	0	132	0	0	0	0
DS_Ewp-Lo:Hi	0	0	537	0	354	2789	2723

5.3.4 View results and analysis

Occupants prefer to have a window with a view to the outside rather than not [Figure **5-18**]. The view quality in this study is evaluated by the number of hours for which the shade is not deployed. Figure **5-19** and appendix **B-23** shows the number of hours that a view is present due to the shades not being activated under each control strategy.

For a west-facing window, a view is available 61-83% of the time depending on the control strategies used, while it is 37-81% for a south-facing window. It is interesting to note that sunlight penetration control (*ApAz_ctr)* is impacted by latitude only on the south side, with more Northern cities requiring the shade more often on a south facade. Work plane illuminance control (*Ewp_ctr*) closes the shade the least amount of time, and in some cases, this permits 33% more hours of view than the next closest case.

Fig 5-18: A room showing translucent shades when open (left), provide view to the outside but also the possibility for direct sunlight penetration. When shades are closed (right), the view is blocked but this prevents direct sunlight penetration.

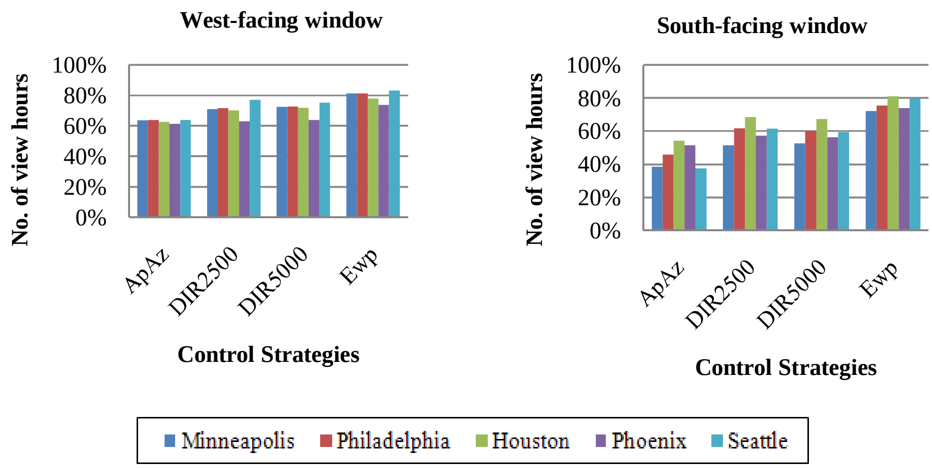


Fig 5-19: The number of hours that a view is available under the different control strategies for west and south-facing windows in the five test cities.

5.4 References

IESNA (2000). The IESNA Lighting Handbook, 9th Edition. New York.

Chapter 6

CONCLUSIONS AND DISCUSSIONS

This thesis explored the impact of translucent fabric shades and various shade control strategies with integrated lighting control on both energy savings and visual quality. Since shades provide a way for building occupants to control sunlight penetration and reduce heat gain, regulating shades affects building energy. Currently, it is not particularly clear how shades and shade control strategies affect overall building energy savings. There have been limited studies investigating the impact of shades on building energy consumption and visual quality. The shade's material properties, application and characterizations in these studies do not reflect modern shades and their application. Moreover, even with the potential impact on energy, shades are not normally included in energy model studies during the design process. This is because the occupants normally leave shades closed a large fraction of the time, but models are generally performed with no shades. With automatic control of shades, this problem can be addressed.

Since shades also impact the indoor lighting environment in a building, shade control strategies should provide acceptable visual quality. Visual quality was studied using different quality indices such as daylight glare index (DGI), work plane illuminance, luminance ratios and view.

This study had a goal to further the understanding of shading and control options to save energy while providing a quality visual environment in a building. To achieve this goal, a study was conducted to analyze the impact of shades with automatic shade control strategies on heating, cooling, lighting and total energy use and savings.

These impacts were analyzed through variations in building parameters such as geometry, orientation, site climate, glazing/shade properties, and shade control strategies with integrated lighting control.

A simulation-based approach using the EnergyPlus energy simulation program was used to test performance across these parameters. Daylight simulation programs, AGI32, and DAYSIM were also used to analyze visual quality. Different shade control strategies and integrated lighting control were considered with two translucent fabric shades available for use in commercial buildings.

The following sections summarize the conclusions of this work.

6.1 Impact of translucent shade control strategies on energy savings

The study was conducted on two levels of analysis: at the building level and at the room level.

6.1.1 On the building level with standard (non-Low-E) insulated windows

At the building level, the goal was to determine the impact of shades as it would occur in **an existing building** with standard double-pane clear windows (Window A, SHGC 0.70/U=2.68/Tvis=0.79) with two different window areas (WWR =0.20 and WWR=0.40). Shades were controlled to be closed all day, (*DN*) with and without lighting controls to determine the impact under the different parameters. A comparison was made to a no-shade base case (*NS*), which had no lighting control as is normally applied in building simulations during the preliminary stages of design. Two shades were used in the study, white shades (*WS*, T_{vis} =0.14 / ρ=0.71) and dark shades (*DS*, T_{vis}=0.04/ ρ=0.05). Five different cities throughout the United States: Philadelphia (PA), Minneapolis (MN), Seattle (WA), Houston (TX) and Phoenix (AZ) were considered.

1. When shades are closed all the time without lighting control, shades benefit the cooling-dominated region (hot climate) more than the heating-dominated region (cold climate). The total energy savings were 5% to 13% for white shades in a hot climate and 1% to 5% in a cold climate for both WWR=0.20 and 0.40. Dark shades showed no total energy savings, and in certain cases higher energy consumption. The energy savings in the hot climate resulted from savings in the cooling energy.

2. White shades with higher transmittance (Tvis=0.14) gave better savings (1% to 13% savings) overall compared to dark shades (less than 1% savings) with a lower transmittance (Tvis=0.04). White shades increased cooling energy savings compared to the base case while heating energy losses also occured. Dark shades showed a loss in total energy (-0.1% to -1%) due to losses in heating or cooling energy depending on the sites.

3. When shades are used all day, energy savings are greater for higher window areas (WWR=0.40), but more energy consumption also occurs with higher WWR compared to a lower WWR. For WWR=0.40, total energy savings ranged from 1% to 13% while for WWR=0.2, total energy savings ranged from 1% to 7% across all cities. The WWR=0.40 building energy consumption was approximately 8-11% higher than WWR=0.20 energy consumption.

4. By integrating lighting control with the closed shades (*DN_ctr*), the total energy savings increased in both the hot and cold climates. The total energy savings improved from 8-13% to 14-19% for white shades in the hot climate and from 1-5% to 4-10% for white shades in the cold climate in all geometries. The total energy savings more than doubled relative to the closed shade with no lighting control (*DN*). The increased benefits occur from the additional cooling energy savings from the reduced electric lighting heat gain.

5. The impact of a shade closed all day with integrated lighting control (*DN_ctr*) was investigated in the perimeter and core zones at the building level. The highest lighting energy savings in the perimeter zone was 43% to 47% while the cooling energy savings was 34% to 36% with white shades when compared to a case without shades.

6. Changes in the building geometry resulted in different total energy use. A long thin building facing east and west showed the greatest improvement due to shade use but also the highest energy use for the base case when compared to both a long thin building facing north-south and a square building. This is because the long thin building has more window area compared to the square building and by facing the long facade east and west, the solar load increased.

7. A test was conducted to determine the change in total energy for closed shades from the standpoint of envelope loads. Shades were closed all day during summer months (April-September) and shades were left open for winter months (October- March). Two test cities, Phoenix and Minneapolis, and two shade colors were tested. The results showed a further reduction in total energy in the cold climate (increase from 3% savings with closed shades all the time to 5% savings with seasonally closed shades) while the opposite occurred in the hot climate (a decrease from 16% savings with closed shades all the time to 7% savings when seasonal controlled). The total energy savings were less in the cold climate compared to the hot climate. This was only true with white shades. Dark shades used more energy with seasonal control of shades for both climates. Seasonal control did not work well in the hot climate because cooling is required for much of the year.

6.1.2 On the room level with higher performance windows

At the room level, this study addressed the impact of shades with higher performance windows as it would occur in new buildings. The double pane windows used in this study were non low-E window B (SHGC=0.38/ U=2.73/ Tvis=0.60), low-E window C (SHGC=0.24/ U=1.62/ Tvis=0.60) and low-E window D (SHGC=0.28/ U=1.61/ Tvis=0.64). Window A was simulated as a case without shades only for comparisons.

The studies were done at the room level for a private office with a WWR of 0.40 for each orientation. The heating, cooling, lighting and total energy use and savings were compared with the base case (*NS)*, a room without shades or lighting control) for each window condition. Various shade control strategies were tested to optimize the energy savings, these are:

- Shades closed all day without lighting controls (*DN*)
- Shades closed all day with lighting controls (*DN_ctr*)

For automated control of shades, two strategies were tested:

- Shades controlled to close during the time of the day when direct sunlight could strike the window, with automatic lighting control (*EMWA_ctr)*. The shades were closed on the east façade in the morning (7am-1pm DST), on the west façade in the afternoon (1pm-7pm DST), with no shading on the north and all-day shading on the south facade.
- In another set of options, shades were controlled to close when solar radiation reached one of three setpoint conditions (*Solxxx_ctr*): a low solar set point, (*Sol189*) 189 W/m^2 (60 Btu/hr-ft^2); a medium solar set point, (*Sol378*) 378 Btu/hr-ft^2 (40Btu/hr-ft^2); and a high solar set point, (*Sol630*) 630 W/m^2 (200 Btu/hr-ft^2).

Two shades were also used in this study, white shades (*WS*, T_{vis} =0.14 / ρ=0.71) and dark shades (*DS*, T_{vis}=0.04/ ρ=0.05). Five cities, Philadelphia (PA), Minneapolis (MN), Seattle (WA), Houston (TX) and Phoenix (AZ) were investigated. Window D was used in all cities while Window B was used only in Philadelphia, Minneapolis and Seattle. Window C was used only in Houston and Phoenix according to recommendations from the ASHRAE/IESNA 90.1-2004 Standard.

The results showed that:

1. With better windows, the energy savings impact from shades is reduced. When windows were changed from a standard double-pane clear window (Window A) to a better performance window (low-E) such as window D, an energy savings of 8-25% was already realized without the impact of shades. The savings vary based on the window type. The additional shade savings were in the range of 1-10% with shades used all day (*DN*) when compared to the base case with window A.

For automatic control, the following findings were reported with respect to the base case with window D and a WWR=0.40.

2. With shade use all day, more heating energy was required compared to the base case. White shades required more heating energy than dark shades.

3. Total energy savings in the range of 7-35% occurred on a room level with automatic control of white shades in the hot climate across all orientations compared to when shades were closed all day with or without lighting controls (*DN*, *DN_ctr*).

4. Regarding orientation, the south orientation showed the least total energy savings for both types of automatic control (1-17% in the cold climate, 7-25% in the hot climate) due to large fraction of time shades are used to provide visual comfort. While the west and east provided greater benefit due to less time that shades are required to provide comfort with about 5-14% total energy savings in the cold and 11-31% total energy savings in the hot climate.

5. The north façade showed the highest total energy savings for both control strategies (*EMWA_ctr* and *Solxxx_ctr*) compared to the case with shades closed all the time (*DN*). This is because low solar radiation permitted the shades to be open much of the time.

6. Total energy savings increase as the levels of daylight delivered to the space increase. Lighting energy savings (7-25% of total energy) were the largest contributor to total energy savings when integrated lighting control was used.

7. The incident radiation at which the shade is lowered should be set as high as possible to receive maximum benefit from lighting energy savings. The high solar control setpoint with white shades provided maximum energy savings (19-35%) in all cities with the most significant savings in a hot climate. In Houston, the medium solar control setting with white shades also provided equally good results (35% savings).

8. White shades gave similar total energy savings compared to dark shades in all cases when used with the solar radiation control strategies. White shades had only about 1% higher total energy savings than dark shades.

9. A hot climate also provided higher total energy savings than the cold climate with white shades. For both automatic control types, about 70-80% of these savings resulted from the lighting energy savings.

6.2 Impact of translucent shade control strategies on energy savings and visual quality with Low-E windows

This section investigated the use of automatic control strategies to optimize the lighting energy savings, which is the main contributor to the total energy savings while also providing acceptable visual quality. This study was performed at a room level with the low-E windows (window D) and WWR=0.40. A cold climate and a hot climate city, Minneapolis (MN) and Phoenix (AZ), were selected for study. The proportion of heating, cooling, and lighting energy use for a test room in Minneapolis is about 70%/15%/15%. While the energy proportion for Phoenix is about 10%/60%/30%. These proportions differ slightly across building orientations.

The total, heating, cooling and lighting energy use reported were compared with the base case (*NS),* a case without shades or lighting controls) for the study conditions. Automatic shade control strategies in this section were developed with the aim to:

1) Limit or eliminate sunlight penetration beyond a distance of 0.60 m (2ft) from the windows on all surfaces.
2) Improve total energy savings, especially lighting energy savings, by leaving the shades open as much as possible without negatively affecting visual quality. In order to do so, the exterior direct normal illuminance values were also used as a control parameter.
3) Maintain the interior illuminance level at a critical point on the work plane within a useful illuminance range. The recommended range for daylight illuminance is between 100 and 2000 lux (10 to 200 fc).
4) Reduce the number of hours with poor visual quality. In this study, daylight glare index (DGI) and luminance ratios were considered.
5) Maximize the number of view hours achieved (i.e. hours when the shade is up) while still providing a quality lighting condition.

All of these criteria are used in the development of automatic control strategies but not necessary always addressed. The automatic shade control strategies that were studied using the above criteria are as follows:

- Sunlight penetration control ($A_pA_z\_ctr$): This control eliminates direct sunlight beyond a 0.6m (2ft) distance from the windows. Shades are fully closed when the profile angle (A_p) is between 0 and 72 degrees and the building elevation azimuth angle (A_z) is less than 72 degrees, regardless of cloud cover condition.

- Direct normal illuminance control (*DIR2500_ctr* and *DIR5000_ctr*): These control strategies adjust shades based on sunlight penetration, as in A_pA_z control, but open the shades when the direct normal exterior illuminance is below 2500 lux (*DIR2500_ctr*) and 5000 lux (*DIR5000_ctr*) respectively, as the sky conditions approach overcast.
- Work plane illuminance control (*Ewp_ctr*): This control strategy applied shades to reduce daylight levels within the space when the interior illuminance exceeded 2000 lux at the critical work plane point.

The analysis addressed the energy savings and visual quality on a west and south façade in Minneapolis and Phoenix for both the white (WS) and dark shades (DS).

The results show that:

1. The difference in lighting energy consumption between automatic control strategies occurs due to a difference in the number of hours that shades were left open during low illuminance conditions, such as an overcast sky. The more the shades were left open, the higher the lighting energy savings. The lighting energy savings for these automatic control strategies cases were shown to be two to five times higher than when the shade was used all day with lighting control (*DN_ctr*), depending on shade color and window orientations.

2. The use of work plane illuminance control (*Ewp_ctr*) shows good total energy savings (6-22%) and acceptable visual quality, especially for work plane illuminance and view, over when the shades are closed all day with no lighting control for selected cities and orientations. This condition generally permitted the shades to be up the most though it negatively affected visual quality for some measures such as DGI and luminance ratios.

3. For lighting energy savings, work plane illuminance control strategies (*Ewp_ctr*) with white shades and integrated lighting control can provide up to 80% lighting energy savings (or about 22% of total energy savings) on an overcast day on select cities when compared to the base case on the west facade.

4. When shades are closed all day (*DN*), an acceptable level of daylight glare index (DGI) is achieved at nearly all times. This, however, considers that the occupant is oriented to face the window, which is an unlikely office arrangement. Automatic control strategies might still, therefore, provide acceptable comfort with proper worker orientation.

5. Luminance ratio analysis of a clear and an overcast day for a space without electric lighting shows that acceptable luminance values within the recommended ratios (1:3 and 3:1 for adjacent surfaces and 1:10 and 10:1 for distant surfaces) can be achieved under a clear sky with white shades. For the overcast sky, the case without shades provides acceptable luminance ratios across surfaces while both white and dark shades showed problems with the VDT task. This is due to the high luminance applied in contrast to the darker surroundings. Electric lighting will help reduce these ratios.

6. An annual luminance ratio analysis with electric lighting shows that the room itself exceeded the recommended values for the VDT task and the adjacent surround without the impact of shades at a nighttime condition. By using shades and regulating them, increased room surface luminances helped improve these luminance ratios. The case without shades is not the best for an occupant's visual quality due to the excessive luminance ratios that occur in many hours of the year for all task to adjacent and distant surface luminance ratios.

7. When shades are closed all day (*DN*), acceptable luminance ratios and DGI are obtained at nearly all times for both proximate and distant surfaces. However, the view hours for this type of control are zero.

8. A work plane illuminance control strategy provides the best luminance ratios on adjacent surfaces (1:3 or 3:1) and performs the same for white and dark shades. For distant surfaces, all control strategies performed similarly with the least hours exceeding recommended ratios for the direct normal illuminance control at 2500 lux. South-facing windows had more hours of luminance ratios exceeding the recommended value than did west-facing windows.

9. The automatic shade control strategies, especially the work plane illuminance control strategy (*Ewp_ctr*), provided adequate view hours for the occupants. A view was available between 61-83% of the hours for a west-facing window while about 37-81% view hours were obtained for a south-facing window. The use of a sun penetration control strategy provided the lowest number of view hours while the use of work plane illuminance control provided the greatest view hours among these automatic control strategies. It is interesting to note that sunlight penetration control (*ApAz_ctr)* impacts view hours based on latitude only on the south side, with more Northern cities requiring shades more often. The work plane illuminance control (*Ewp_ctr*) closed the shade the least amount of time.

6.3 Comparisons of annual total energy savings across all control strategies on the room level

1. White shades showed better performance than dark shades in almost all cases. This is due to the higher lighting energy savings that also provide for cooling energy reduction. However, heating energy use increased in the cold climate region. Overall, total energy savings were achieved.

2. The energy benefits of shades are more pronounced in a hot climate than in a cold climate.

3. Automatic shade control strategies provide greater total energy savings (3-30%) compared to when shades are closed all day (1-12%).

4. The total energy savings were optimized using a solar radiation control strategy and a work plane illuminance control strategy combined with integrated lighting control. The work plane illuminance control strategy showed good visual quality relative to work plane illuminance and view.

5. The impact of translucent fabric shades and control strategies show significant savings for total, cooling and lighting energy use for the case study building on both the building level and the room level. For the building level with standard (non-Low-E) windows, the maximum total energy savings is 19% for white shades closed all day with lighting control (*DN_WS_ctr*) and WWR=0.40 for Phoenix. And for the room level with high performance windows, 35% total energy savings was obtained from the east-facing windows for white shades with a high solar setpoint control strategy (*WS_Sol630_ctr*), window D and WWR=0.40 for Houston.

Both heating and cooling-dominated climates show higher total energy savings when applying shade control strategies with white shades. These total energy savings may also impact building systems and help reduce the size of mechanical cooling systems if shade and shade control strategies are considered during the design process. Hence, the analysis of savings from shades and lighting controls may be further applied to building design and yield important savings.

6.4 Discussions

This study clearly shows that shades and shade control strategies can impact building energy differently based on the building design parameters.

The use of automatic control of shades with integrated lighting control provides higher energy savings over the infrequent adjustment of shades and no lighting control. The higher energy savings results from the lighting energy savings that occur when shades are left opened during times when they are not needed.

In addition, the cooling energy savings received from the reduction of solar heat gain and the reduction of heat from the lights adds to the total energy savings, especially in the hot climate regions. Shades provide more energy savings in a hot climate than cold climate but are needed for visual quality in both climates.

Light-colored shades show a greater total energy savings in all climates when compared to the dark-colored shades with lower transmittance and reflectance.

The use of shades all day without integrated lighting control is not recommended because it provides only limited savings in certain conditions and sometimes may produce a loss in savings and destroys the view. In many cases, this might be what occurs with normal occupant behavior.

An automatic shade and lighting control strategy with a white shade that leaves the shades open a maximum number of hours and is based on work plane illuminance is shown to provide the highest energy savings. However, the visual quality of occupants within the space is diminished especially on DGI and luminance ratios.

Shade control should be configured differently by orientation and other building parameters. Hence, a detailed analysis should be addressed early in the design of a building. In hot climates, south orientation provides less energy savings than other orientations due to the duration of shade use is higher than on other orientations. For the cold climate, the results depend on the glazing performance.

Better performance glazing, when used with shades, show smaller energy savings compared to regular glazing. Since lighting energy savings is the main contributor to total energy savings, shade control strategies to optimize energy savings and provide visual quality can be developed. The results suggested that higher lighting energy savings can be optimized by leaving shades to open during the low illuminance conditions, such as overcast sky, or by controlling shades to open when the work plane illuminance is below a certain level.

The recommended shade control strategies that can be implemented in building systems especially on the east, west and south facades are a solar radiation control strategy and work plane illuminance control strategy with the following equipment:

- Solar radiometer (an exterior sensor per orientation) for real time solar radiation measurement
- Integrated lighting control system with closed-loop or dual-loop photosensors (an interior sensor) for maximizing the lighting energy savings by monitoring work plane illuminance.

- A central building integrated control system with an automatic shade and lighting control strategy that can be tailored to orientation differences for the whole building.
- A system override that allows users to alter the position of shades when desired. The systems can be timed or coupled with occupancy sensors to override back to the original settings to maximize the use of daylight or minimize envelope loads. However, this type of control should be carefully designed because sudden changes in daylight levels can be annoying to the occupants.

6.5 Future work

This dissertation only covers a few of the important aspects of shades regarding their direct impact on building energy performance and visual quality. The results applied only to certain cities, but the method of analysis should provide some guidance to apply to other regions internationally.

Proper control of shades will improve visual quality for the occupants. Future work should address how occupants respond to different shade control strategies and to different window and room surface luminances in an attempt to further qualify approaches that save energy and are accepted by the occupants.

Laboratory and field studies on actual performance of shades such as their effect on solar heat gain coefficient (SHGC) and thermal transmission (U-factor) and the potential thermal impact of shades at night are needed since these parameters were considered in this study based via simulation alone.

Appendix A

Detailed results for chapter 4

Table A-1: Energy usage (kWh/m^2-yr) on different building geometries in cold climate, MN, PA and WA, with closed shade all day, no lighting control (*DN*), two shade colors white and dark shades (*WS*, *DS*) and window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 (Table 4-1).

PA_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	67.09	72.72	66.47	65.18	72.55	64.90	67.64	74.16	67.11
Cooling	64.21	52.87	65.20	65.59	53.08	66.36	72.52	57.20	72.97
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	161.64	155.93	162.01	161.12	155.97	161.60	170.50	161.70	170.43

MN_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	135.00	141.86	133.49	133.40	142.67	132.14	136.89	144.62	135.41
Cooling	51.58	41.42	52.36	52.20	41.33	52.72	59.59	45.55	59.97
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	216.92	213.63	216.19	215.94	214.34	215.20	226.82	220.52	225.72

WA_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	65.32	69.81	64.46	65.35	70.98	64.54	65.83	71.09	65.03
Cooling	30.16	22.17	31.51	31.01	22.25	32.10	35.70	24.68	36.91
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	125.82	122.32	126.31	126.70	123.57	126.98	131.88	126.11	132.29

TX_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	11.06	12.77	11.04	9.44	11.81	9.16	9.96	12.15	9.59
Cooling	130.04	113.61	130.57	129.66	113.10	130.25	139.26	118.74	139.41
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	171.45	156.72	171.96	169.44	155.25	169.74	179.56	161.23	179.35

AZ_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	5.42	6.74	5.60	3.63	5.53	3.60	4.17	6.73	5.35
Cooling	189.72	165.27	189.44	188.65	163.94	188.15	204.38	176.27	207.45
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	225.48	202.35	225.38	222.62	199.81	222.09	238.89	213.34	243.15

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix
A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)
20,40 - Window-to-wall ratio 0.20 to 0.40

Table A-2: Energy usage (kWh/ m^2-yr) on different building geometries in cold climate, MN, PA and WA, with closed shade all day, no lighting control (*DN*), two shade colors white and dark shades (*WS*, *DS*) and window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.20 (Table 4-2).

PA_A_20									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	68.06	71.61	67.86	67.27	71.87	67.18	68.87	71.87	67.18
Cooling	52.75	47.11	52.64	52.91	47.00	52.73	56.94	47.00	52.73
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	151.15	149.07	150.84	150.52	149.21	150.25	156.16	149.21	150.25

MN_A_20									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	133.65	137.89	133.18	133.36	138.89	132.98	135.30	138.89	132.98
Cooling	41.39	36.31	41.28	41.27	36.05	41.10	45.38	36.05	41.10
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	205.38	204.54	204.80	204.97	205.28	204.42	211.02	205.28	204.42

WA_A_20									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	64.91	67.87	64.65	65.40	68.99	65.14	65.56	68.99	65.14
Cooling	21.96	18.26	22.26	21.99	18.06	22.20	24.37	18.06	22.20
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	117.21	116.47	117.25	117.73	117.39	117.68	120.27	117.39	117.68

TX_A_20									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	11.36	12.54	11.40	10.51	11.97	10.42	10.87	11.97	10.42
Cooling	112.53	103.94	112.13	111.44	103.05	111.27	116.88	103.05	111.27
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	154.23	146.82	153.87	152.30	145.37	152.04	158.09	145.37	152.04

AZ_A_20									
	Square			Long thin N-S			Long thin E-W		
	NS	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*	*DN_NS*	*DN_WS*	*DN_DS*
Heating	5.59	6.58	5.73	4.52	5.92	4.52	5.04	5.92	4.52
Cooling	162.62	149.91	161.61	160.65	148.31	159.81	169.58	148.31	159.81
Lighting	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34	30.34
Total	198.55	186.84	197.69	195.51	184.58	194.67	204.96	184.58	194.67

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix
A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)
20,40 - Window-to-wall ratio 0.20 to 0.40

Table A-3: Envelope loads and internal gains in Minneapolis, with window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 without shades (*NS*) (Figure 4-1).

Date/Time	Glazing	Walls	Ceilings (int)	Floors (int)	Partitions (int)	Mech Vent + Nat Vent + Infiltration	External Infiltration	External Vent.
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	ac/h	kWh/ m^2-yr	kWh/ m^2-yr
Jan	-6.56	-1.50	0.01	0.05	0.01	1.36	-14.17	-27.18
Feb	-4.57	-1.10	-0.02	-0.08	-0.02	1.32	-9.69	-18.79
Mar	-3.73	-0.84	0.00	0.05	0.00	1.28	-7.74	-12.05
Apr	-2.83	-0.64	-0.02	-0.12	-0.02	1.35	-5.92	-9.93
May	-1.82	-0.35	-0.01	-0.08	-0.01	1.36	-3.54	-3.79
Jun	-1.02	-0.21	-0.03	-0.15	-0.03	1.27	-2.10	0.28
Jul	-0.51	0.02	0.02	0.11	0.02	1.36	-1.14	1.95
Aug	-1.07	-0.17	0.00	0.01	0.00	1.32	-2.16	-0.34
Sep	-1.66	-0.30	0.01	0.03	0.01	1.31	-3.23	-2.42
Oct	-2.92	-0.60	0.01	0.07	0.01	1.36	-5.69	-9.21
Nov	-3.95	-0.85	0.04	0.20	0.03	1.31	-8.04	-14.93
Dec	-5.62	-1.34	-0.02	-0.08	-0.01	1.32	-11.74	-22.16

Date/Time	General Lighting	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone/Sys Sensible Heating	Zone/Sys Sensible Cooling
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr
Jan	2.67	4.49	1.74	3.71	37.26	0.00
Feb	2.33	3.92	1.52	4.17	22.88	-0.01
Mar	2.44	4.15	1.58	5.17	11.66	-0.18
Apr	2.56	4.30	1.62	5.67	8.11	-2.30
May	2.67	4.49	1.60	6.32	0.71	-5.79
Jun	2.33	3.96	1.36	6.40	0.05	-10.51
Jul	2.67	4.49	1.55	6.33	0.00	-15.21
Aug	2.56	4.32	1.49	6.05	0.00	-10.40
Sep	2.44	4.13	1.46	5.14	1.34	-6.62
Oct	2.67	4.49	1.71	4.53	5.92	-0.53
Nov	2.44	4.13	1.59	3.04	16.81	-0.05
Dec	2.56	4.32	1.67	2.66	30.26	0.00

Table A-4: Envelope loads and internal gains in Minneapolis, with window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 with white shades (*WS*) (Figure 4-2).

Date/Time	Glazing	Walls	Ceilings (int)	Floors (int)	Partitions (int)	Mech Vent + Nat Vent + Infiltration	External Infiltration	External Vent.
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	ac/h	kWh/ m^2-yr	kWh/ m^2-yr
Jan	-5.59	-1.70	0.01	0.05	0.02	1.35	-14.13	-27.12
Feb	-3.25	-1.18	-0.01	-0.06	-0.02	1.32	-9.60	-18.74
Mar	-1.75	-0.82	0.01	0.07	0.01	1.28	-7.57	-11.98
Apr	-0.33	-0.57	-0.03	-0.13	-0.03	1.34	-5.69	-9.86
May	1.09	-0.21	-0.01	-0.09	-0.02	1.35	-3.31	-3.74
Jun	1.99	-0.01	-0.02	-0.11	-0.03	1.27	-1.88	0.29
Jul	2.46	0.20	0.01	0.08	0.02	1.35	-0.93	1.94
Aug	1.68	0.01	0.01	0.04	0.01	1.32	-1.92	-0.33
Sep	0.53	-0.21	0.00	0.01	0.00	1.31	-3.00	-2.40
Oct	-1.13	-0.58	0.01	0.07	0.02	1.35	-5.43	-9.09
Nov	-2.97	-0.94	0.04	0.21	0.04	1.31	-7.95	-14.89
Dec	-4.94	-1.54	-0.02	-0.11	-0.02	1.32	-11.70	-22.11

Date/Time	General Lighting	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone/Sys Sensible Heating	Zone/Sys Sensible Cooling
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr
Jan	2.67	4.49	1.74	0.77	39.19	0.00
Feb	2.33	3.92	1.52	0.93	24.56	0.00
Mar	2.44	4.15	1.59	1.26	13.04	-0.05
Apr	2.56	4.30	1.63	1.52	8.85	-1.86
May	2.67	4.49	1.60	1.76	0.88	-4.86
Jun	2.33	3.96	1.36	1.82	0.07	-9.58
Jul	2.67	4.49	1.55	1.79	0.00	-14.13
Aug	2.56	4.32	1.49	1.65	0.01	-9.36
Sep	2.44	4.13	1.47	1.30	1.56	-5.60
Oct	2.67	4.49	1.73	1.06	6.66	-0.12
Nov	2.44	4.13	1.59	0.64	18.02	0.00
Dec	2.56	4.32	1.67	0.52	31.78	0.00

Table A-5: Envelope loads and internal gains in Minneapolis, with window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 with dark shades (*DS*) (Figure 4-3).

Date/Time	Glazing	Walls	Ceilings (int)	Floors (int)	Partitions (int)	Mech Vent + Nat Vent + Infiltration	External Infiltration	External Vent.
	kWh/ m²-yr	kWh/ m²-yr	kWh/ m²-yr	kWh/ m²-yr	kWh/ m²-yr	ac/h	kWh/ m²-yr	kWh/ m²-yr
Jan	-3.47	-1.71	0.01	0.05	0.02	1.35	-14.16	-27.12
Feb	-0.72	-1.21	-0.01	-0.06	-0.02	1.32	-9.67	-18.75
Mar	1.60	-0.89	0.00	0.02	0.00	1.28	-7.76	-12.05
Apr	3.72	-0.61	-0.02	-0.10	-0.02	1.34	-5.96	-9.97
May	5.77	-0.27	-0.01	-0.08	-0.02	1.35	-3.64	-3.83
Jun	6.81	-0.11	-0.03	-0.17	-0.04	1.27	-2.24	0.28
Jul	7.24	0.16	0.02	0.14	0.03	1.35	-1.21	1.94
Aug	6.08	-0.07	0.00	0.00	0.00	1.32	-2.23	-0.35
Sep	3.97	-0.26	0.01	0.04	0.01	1.31	-3.26	-2.43
Oct	1.61	-0.63	0.01	0.07	0.02	1.35	-5.70	-9.23
Nov	-1.23	-0.96	0.04	0.20	0.04	1.31	-8.02	-14.90
Dec	-3.50	-1.54	-0.02	-0.09	-0.02	1.32	-11.73	-22.11

Date/Time	General Lighting	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone/Sys Sensible Heating	Zone/Sys Sensible Cooling
	kWh/ m²-yr	kWh/ m²-yr	kWh/ m²-yr	kWh/ m²-yr	kWh/ m²-yr	kWh/ m²-yr
Jan	2.67	4.49	1.74	0.11	37.79	0.00
Feb	2.33	3.92	1.52	0.14	22.96	-0.02
Mar	2.44	4.15	1.58	0.18	11.38	-0.24
Apr	2.56	4.30	1.61	0.22	7.70	-3.07
May	2.67	4.49	1.59	0.26	0.61	-7.29
Jun	2.33	3.96	1.36	0.27	0.04	-12.26
Jul	2.67	4.49	1.55	0.26	0.00	-17.14
Aug	2.56	4.32	1.49	0.24	0.00	-11.87
Sep	2.44	4.13	1.46	0.19	1.31	-7.41
Oct	2.67	4.49	1.71	0.15	5.79	-0.61
Nov	2.44	4.13	1.59	0.09	17.02	-0.05
Dec	2.56	4.32	1.67	0.08	30.82	0.00

Table A-6: Envelope loads and internal gains in Phoenix, with window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 without shades (*NS*) (Figure 4-4).

Date/Time	Glazing	Walls	Ceilings (int)	Floors (int)	Partitions (int)	Mech Vent + Nat Vent + Infiltration	External Infiltration	External Vent.
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	ac/h	kWh/ m^2-yr	kWh/ m^2-yr
Jan	-2.31	-0.44	0.01	0.04	0.01	1.36	-4.33	-5.41
Feb	-1.57	-0.34	-0.02	-0.11	-0.02	1.32	-3.06	-2.76
Mar	-1.70	-0.27	0.01	0.04	0.01	1.28	-3.19	-2.39
Apr	-0.63	-0.07	-0.02	-0.07	-0.02	1.35	-1.14	2.41
May	0.11	0.12	0.00	0.01	0.00	1.36	0.09	5.60
Jun	1.17	0.27	-0.05	-0.23	-0.04	1.27	1.84	8.94
Jul	1.76	0.56	0.05	0.23	0.04	1.36	2.58	10.65
Aug	1.37	0.33	-0.03	-0.15	-0.03	1.32	2.02	9.13
Sep	0.54	0.28	0.02	0.07	0.02	1.31	0.81	6.58
Oct	-0.33	0.07	0.02	0.13	0.02	1.36	-0.66	3.73
Nov	-1.46	-0.25	0.01	0.02	0.01	1.31	-2.72	-1.20
Dec	-2.40	-0.46	0.01	0.04	0.01	1.32	-4.68	-6.02

Date/Time	General Lighting	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone/Sys Sensible Heating	Zone/Sys Sensible Cooling
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr
Jan	2.67	4.49	1.63	5.78	1.51	-3.17
Feb	2.33	3.92	1.40	5.56	0.87	-5.81
Mar	2.44	4.15	1.45	6.63	0.64	-7.48
Apr	2.56	4.30	1.49	6.95	0.08	-15.54
May	2.67	4.49	1.55	7.08	0.00	-21.43
Jun	2.33	3.96	1.35	6.94	0.00	-26.19
Jul	2.67	4.49	1.55	6.52	0.00	-30.89
Aug	2.56	4.32	1.48	6.82	0.00	-27.59
Sep	2.44	4.13	1.42	6.84	0.00	-22.92
Oct	2.67	4.49	1.55	6.64	0.00	-18.02
Nov	2.44	4.13	1.43	6.13	0.06	-8.18
Dec	2.56	4.32	1.58	5.76	2.26	-2.50

Table A-7: Envelope loads and internal gains in Phoenix, with window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 with white shades (*WS*) (Figure 4-5).

Date/Time	Glazing	Walls	Ceilings (int)	Floors (int)	Partitions (int)	Mech Vent + Nat Vent + Infiltration	External Infiltration	External Vent.
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	ac/h	kWh/ m^2-yr	kWh/ m^2-yr
Jan	-0.20	-0.38	0.01	0.04	0.01	1.35	-4.01	-5.32
Feb	0.59	-0.25	-0.02	-0.11	-0.03	1.32	-2.80	-2.70
Mar	1.21	-0.10	0.01	0.05	0.02	1.28	-2.90	-2.36
Apr	2.69	0.12	-0.02	-0.08	-0.02	1.34	-0.92	2.43
May	3.72	0.38	0.00	0.01	0.00	1.35	0.28	5.59
Jun	4.82	0.58	-0.04	-0.21	-0.05	1.27	2.05	8.93
Jul	5.13	0.85	0.04	0.20	0.04	1.35	2.79	10.64
Aug	4.80	0.63	-0.03	-0.12	-0.03	1.32	2.24	9.12
Sep	3.70	0.51	0.02	0.06	0.02	1.31	1.07	6.57
Oct	2.37	0.24	0.02	0.12	0.02	1.35	-0.40	3.73
Nov	0.79	-0.13	0.01	0.05	0.01	1.31	-2.43	-1.18
Dec	-0.31	-0.41	0.00	0.01	0.00	1.32	-4.33	-5.91

Date/Time	General Lighting	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone/Sys Sensible Heating	Zone/Sys Sensible Cooling
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr
Jan	2.67	4.49	1.64	1.28	1.89	-1.86
Feb	2.33	3.92	1.41	1.31	1.10	-4.52
Mar	2.44	4.15	1.45	1.75	0.74	-6.25
Apr	2.56	4.30	1.50	1.99	0.11	-14.44
May	2.67	4.49	1.55	2.15	0.00	-20.69
Jun	2.33	3.96	1.35	2.13	0.00	-25.72
Jul	2.67	4.49	1.55	1.95	0.00	-30.28
Aug	2.56	4.32	1.48	2.01	0.00	-26.87
Sep	2.44	4.13	1.42	1.86	0.00	-21.70
Oct	2.67	4.49	1.55	1.62	0.01	-16.30
Nov	2.44	4.13	1.43	1.37	0.13	-6.43
Dec	2.56	4.32	1.60	1.24	2.76	-1.24

Table A-8: Envelope loads and internal gains in Phoenix, with window A, standard double clear glazing, SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 with dark shades (D*S*) (Figure 4-6).

Date/Time	Glazing	Walls	Ceilings (int)	Floors (int)	Partitions (int)	Mech Vent + Nat Vent + Infiltration	External Infiltration	External Vent.
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	ac/h	kWh/ m^2-yr	kWh/ m^2-yr
Jan	3.19	-0.44	0.01	0.04	0.01	1.35	-4.26	-5.44
Feb	4.07	-0.31	-0.02	-0.11	-0.03	1.32	-3.04	-2.79
Mar	5.84	-0.19	0.00	0.00	0.01	1.28	-3.25	-2.40
Apr	8.00	0.07	-0.01	-0.04	-0.01	1.34	-1.23	2.40
May	9.48	0.31	0.00	0.01	0.00	1.35	0.00	5.59
Jun	10.38	0.47	-0.05	-0.27	-0.06	1.27	1.70	8.93
Jul	10.26	0.81	0.05	0.26	0.06	1.35	2.52	10.64
Aug	10.08	0.54	-0.04	-0.16	-0.04	1.32	1.97	9.12
Sep	8.58	0.46	0.03	0.09	0.03	1.31	0.77	6.57
Oct	6.71	0.19	0.02	0.14	0.03	1.35	-0.63	3.72
Nov	4.46	-0.20	0.01	0.02	0.01	1.31	-2.65	-1.21
Dec	2.95	-0.46	0.01	0.03	0.01	1.32	-4.61	-6.05

Date/Time	General Lighting	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone/Sys Sensible Heating	Zone/Sys Sensible Cooling
	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr	kWh/ m^2-yr
Jan	2.67	4.49	1.63	0.19	1.50	-3.33
Feb	2.33	3.92	1.39	0.19	0.85	-6.25
Mar	2.44	4.15	1.45	0.25	0.61	-8.70
Apr	2.56	4.30	1.49	0.29	0.07	-17.71
May	2.67	4.49	1.55	0.31	0.00	-24.30
Jun	2.33	3.96	1.35	0.31	0.00	-28.94
Jul	2.67	4.49	1.55	0.28	0.00	-33.53
Aug	2.56	4.32	1.48	0.29	0.00	-30.01
Sep	2.44	4.13	1.42	0.27	0.00	-24.69
Oct	2.67	4.49	1.55	0.24	0.00	-18.99
Nov	2.44	4.13	1.43	0.20	0.07	-8.52
Dec	2.56	4.32	1.58	0.18	2.24	-2.48

Table A-9: Energy usage (kWh/m^2-yr) on different building geometries in cold climate, MN, PA and WA, with closed shade all day and lighting control (*DN_ctr*), two shade colors white and dark shades (*WS*, *DS*) and window A, standard double clear glazing ,SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40 (Table 4-5).

PA_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*
Heating	67.09	74.54	67.08	65.18	74.87	65.69	67.64	74.87	65.69
Cooling	64.21	49.99	63.92	65.59	49.60	64.80	72.52	49.60	64.80
Lighting	30.34	24.85	28.16	30.34	23.55	27.62	30.34	23.55	27.62
Total	161.64	149.37	159.16	161.12	148.02	158.10	170.50	148.02	158.10

MN_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*
Heating	135.00	144.14	134.33	133.40	145.68	133.25	136.89	145.68	133.25
Cooling	51.58	39.00	51.29	52.20	38.45	51.45	59.59	38.45	51.45
Lighting	30.34	24.97	28.19	30.34	23.69	27.65	30.34	23.69	27.65
Total	216.92	208.11	213.80	215.94	207.82	212.35	226.82	207.82	212.35

WA_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*
Heating	65.32	71.72	65.13	65.35	73.45	65.44	65.83	73.45	65.44
Cooling	30.16	20.20	30.55	31.01	19.92	30.97	35.70	19.92	30.97
Lighting	30.34	25.54	28.40	30.34	24.39	27.91	30.34	24.39	27.91
Total	125.82	117.46	124.09	126.70	117.75	124.33	131.88	117.75	124.33

TX_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*
Heating	11.06	13.37	11.22	9.44	13.48	10.97	9.96	13.48	10.97
Cooling	130.04	109.14	128.78	129.66	109.36	130.91	139.26	109.36	130.91
Lighting	30.34	24.54	28.11	30.34	23.25	27.59	30.34	23.25	27.59
Total	171.45	147.06	168.11	169.44	146.09	169.47	179.56	146.09	169.47

AZ_A_40									
	Square			Long thin N-S			Long thin E-W		
	NS	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*	*NS*	*WS_ctr*	*DS_ctr*
Heating	5.42	7.12	5.71	5.03	7.03	5.42	5.06	7.03	5.42
Cooling	189.72	160.05	187.21	194.11	160.93	190.34	209.13	160.93	190.34
Lighting	30.34	24.03	27.76	30.34	22.73	27.26	30.34	22.73	27.26
Total	225.48	191.20	220.69	229.48	190.69	223.02	244.53	190.69	223.02

Note: PA – Philadelphia, MN – Minneapolis, WA – Seattle, TX – Houston and AZ – Phoenix
A – Window (A standard double clear glazing ,SHGC=0.70/ U=0.49/ Tvis=0.79)
20,40 - Window-to-wall ratio 0.20 to 0.40

Table A-10: Results for figure 4-9, Energy usage (kWh/ m^2-yr) in square building in Minneapolis, with closed shade all day with and without lighting control *(DN, DN_ctr)* and window A, standard double clear glazing , SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40.

	Core (929 m^2)					Perimeter (558 m^2)					whole (1,487 m^2)				
	NS	*WS*	*DS*	*WS_ctr*	*DS_ctr*	*NS*	*WS*	*DS*	*WS_ctr*	*DS_ctr*	*NS*	*WS*	*DS*	*WS_ctr*	*DS_ctr*
Heating	122.6	124.9	123.4	125.3	123.5	93.9	102.6	90.7	105.9	91.9	108.2	113.7	107.0	115.6	107.7
Cooling	35.8	32.6	33.8	32.3	33.7	46.9	33.8	50.1	30.3	48.5	41.4	33.2	42.0	31.3	41.1
Lighting	30.3	30.3	30.3	30.3	30.3	18.3	18.3	18.3	9.7	14.9	24.3	24.3	24.3	20.0	22.6
Total	188.7	187.8	187.6	187.9	187.6	159.2	154.8	159.1	145.9	155.3	173.9	171.3	173.3	166.9	171.4

Table A-11: Results for figure 4-10, Energy usage (kWh/ m^2-yr) in long thin (N-S) building in Minneapolis, with closed shade all day with and without lighting control *(DN, DN_ctr)* and window A, standard double clear glazing , SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40.

	Core (886.35 m^2)					Perimeter (934.37 m^2)					whole (1820.7 m^2)				
	NS	*WS*	*DS*	*WS_ctr*	*DS_ctr*	*NS*	*WS*	*DS*	*WS_ctr*	*DS_ctr*	*NS*	*WS*	*DS*	*WS_ctr*	*DS_ctr*
Heating	120.1	122.8	121.1	123.4	121.3	153.3	165.9	149.3	171.3	151.3	136.7	144.4	135.2	147.3	136.3
Cooling	37.9	33.0	34.8	32.5	34.6	81.0	58.0	84.9	51.9	82.1	59.5	45.5	59.9	42.3	58.4
Lighting	29.5	29.5	29.5	29.5	29.5	31.0	31.0	31.0	17.0	25.1	30.3	30.3	30.3	23.3	27.3
Total	187.6	185.3	185.4	185.4	185.5	265.3	254.9	265.2	240.2	258.5	226.5	220.2	225.4	212.9	222.1

Table A-12: Results for figure 4-11, Energy usage (kWh/ m^2-yr) in long thin (E-W) building in Minneapolis, with closed shade all day with and without lighting control *(DN, DN_ctr)* and window A, standard double clear glazing , SHGC=0.70/ U=2.68/ Tvis=0.79, WWR=0.40.

	Core (886.35 m^2)					Perimeter (934.37 m^2)					whole (1820.7 m^2)				
	NS	*WS*	*DS*	*WS_ctr*	*DS_ctr*	*NS*	*WS*	*DS*	*WS_ctr*	*DS_ctr*	*NS*	*WS*	*DS*	*WS_ctr*	*DS_ctr*
Heating	118.7	122.3	120.2	122.7	120.4	147.6	162.7	143.7	168.0	145.7	133.2	142.5	132.0	145.4	133.1
Cooling	35.2	31.8	33.1	31.4	33.0	69.0	50.8	72.1	45.4	69.7	52.1	41.3	52.6	38.4	51.4
Lighting	29.5	29.5	29.5	29.5	29.5	31.0	31.0	31.0	17.8	25.7	30.3	30.3	30.3	23.7	27.6
Total	183.5	183.6	182.8	183.7	182.9	247.7	244.6	246.9	231.2	241.1	215.6	214.1	214.9	207.5	212.0

Table A-13: Results for figure 4-16, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Philadelphia with Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	*NS*	*DN_WS*	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
Heating	83.52	62.45	70.34	76.83	61.13	66.23	76.83
Cooling	23.89	23.78	23.70	21.94	24.78	26.95	21.94
Lighting	30.34	30.34	24.52	5.69	30.34	29.06	5.69
Total	137.74	116.57	118.55	104.46	116.25	122.23	104.46
South							
Heating	59.45	51.16	54.14	54.21	47.04	43.76	54.21
Cooling	28.19	25.90	26.97	26.98	27.76	33.07	26.98
Lighting	30.34	30.34	19.89	19.89	30.34	28.13	19.89
Total	117.98	107.40	101.00	101.08	105.14	104.95	101.08
East							
Heating	73.11	57.78	64.09	66.76	55.29	56.62	66.76
Cooling	28.61	26.04	26.78	25.96	27.85	32.50	25.96
Lighting	30.33	30.33	20.00	11.95	30.33	27.76	11.95
Total	132.05	114.15	110.87	104.67	113.48	116.88	104.67
West							
Heating	75.56	58.87	64.90	68.45	56.80	59.17	68.45
Cooling	28.43	26.06	27.37	26.43	28.05	33.33	26.43
Lighting	30.33	30.33	22.22	12.23	30.33	28.64	12.23
Total	134.32	115.26	114.49	107.11	115.19	121.15	107.11

Table A-14: Results for figure 4-17, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Minneapolis with Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	*NS*	*DN_WS*	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
Heating	114.85	115.56	116.36	124.04	112.83	113.23	123.98
Cooling	16.39	15.28	14.08	12.99	16.75	16.52	13.00
Lighting	30.34	30.34	25.22	5.46	30.34	29.09	5.46
Total	161.58	161.17	155.66	142.49	159.93	158.84	142.44
South							
Heating	87.14	92.72	95.83	96.94	84.78	85.60	85.86
Cooling	21.04	18.61	16.85	16.98	21.96	21.58	21.50
Lighting	30.34	30.34	20.94	19.55	30.34	28.04	27.64
Total	138.52	141.67	133.63	133.47	137.08	135.22	135.00
East							
Heating	104.86	107.17	109.67	113.76	102.65	103.41	108.04
Cooling	21.18	18.78	16.61	16.12	21.94	21.39	19.32
Lighting	30.33	30.33	19.93	10.26	30.33	27.53	16.27
Total	156.37	156.29	146.21	140.14	154.92	152.33	143.63
West							
Heating	106.46	108.52	109.63	114.29	104.47	104.91	110.78
Cooling	20.47	18.56	16.96	16.45	21.75	21.42	19.71
Lighting	30.33	30.33	23.55	13.48	30.33	28.68	17.99
Total	157.27	157.42	150.15	144.23	156.56	155.01	148.48

Table A-15: Results for figure 4-18, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Seattle with Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	*NS*	*DN_WS*	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
Heating	54.33	55.64	56.76	64.01	53.16	53.51	63.92
Cooling	13.24	12.04	10.83	9.32	13.68	13.42	9.34
Lighting	30.24	30.24	25.64	6.13	30.24	29.12	6.13
Total	97.82	97.92	93.24	79.47	97.09	96.05	79.40
South							
Heating	44.99	47.78	49.55	50.27	43.88	44.28	44.50
Cooling	18.25	15.73	13.88	13.91	19.33	18.90	18.80
Lighting	30.24	30.24	23.34	22.18	30.24	28.56	28.27
Total	93.48	93.75	86.77	86.36	93.46	91.74	91.57
East							
Heating	50.72	52.52	54.51	57.79	49.32	49.83	53.84
Cooling	16.73	14.54	12.51	11.62	17.46	16.93	14.42
Lighting	30.24	30.24	22.24	12.77	30.24	28.16	17.27
Total	97.69	97.29	89.25	82.18	97.01	94.92	85.52
West							
Heating	50.84	52.68	53.67	57.63	49.88	50.17	55.63
Cooling	17.89	15.84	14.14	13.48	19.35	18.97	17.06
Lighting	30.24	30.24	24.48	14.99	30.24	28.84	18.72
Total	98.96	98.75	92.29	86.10	99.46	97.98	91.41

Table A-16: Results for figure 4-21, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Houston with Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	*NS*	*DN_WS*	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
Heating	10.33	10.61	10.99	12.52	10.03	10.11	12.49
Cooling	50.12	47.95	45.88	42.45	51.07	50.54	42.48
Lighting	30.34	30.34	26.87	4.37	30.34	29.49	4.37
Total	90.79	88.89	83.73	59.34	91.43	90.14	59.34
South							
Heating	6.43	7.22	7.82	7.93	6.28	6.38	6.43
Cooling	58.74	54.28	51.46	51.06	60.60	59.87	59.74
Lighting	30.34	30.34	21.77	20.43	30.34	28.25	27.88
Total	95.52	91.85	81.05	79.41	97.22	94.50	94.05
East							
Heating	8.23	8.79	9.54	10.11	7.81	7.96	8.69
Cooling	57.58	53.43	49.79	47.72	59.12	58.11	53.75
Lighting	30.33	30.33	21.66	7.71	30.33	28.23	15.21
Total	96.14	92.55	80.98	65.53	97.26	94.29	77.65
West							
Heating	8.88	9.43	9.79	10.68	8.78	8.85	10.18
Cooling	57.71	54.13	51.65	49.57	60.07	59.44	55.56
Lighting	30.33	30.33	24.75	9.30	30.33	28.97	15.76
Total	96.93	93.90	86.18	69.54	99.19	97.26	81.50

Table A-17: Results for figure 4-22, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Phoenix with Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	*NS*	*DN_WS*	*DN_WS_ctr*	*EMWA_WS _ctr*	*DN_DS*	*DN_DS_ctr*	*EMWA_DS_ctr*
Heating	5.81	5.61	5.72	7.96	5.46	5.48	7.94
Cooling	63.27	59.72	58.53	57.14	61.33	61.04	57.18
Lighting	30.34	30.34	26.87	4.37	30.34	29.49	4.37
Total	99.42	95.67	91.12	69.47	97.13	96.02	69.48
South							
Heating	1.74	3.06	3.29	3.45	2.81	2.84	2.99
Cooling	79.09	66.84	64.62	71.03	71.00	70.44	83.20
Lighting	30.34	30.34	23.90	17.70	30.34	28.77	27.14
Total	111.16	100.24	91.81	92.18	104.15	102.06	113.32
East							
Heating	3.65	4.31	4.65	5.35	4.00	4.05	4.53
Cooling	76.97	65.85	62.99	67.13	69.51	68.80	75.33
Lighting	30.33	30.33	21.66	7.71	30.33	28.23	15.21
Total	110.95	100.50	89.29	80.19	103.84	101.07	95.07
West							
Heating	4.21	4.73	4.85	6.24	4.57	4.59	6.04
Cooling	76.31	66.03	64.10	68.14	69.80	69.32	76.33
Lighting	30.33	30.33	24.75	9.30	30.33	28.97	15.76
Total	110.85	101.09	93.70	83.67	104.70	102.89	98.14

Table A-18: Results for table 4-16 and 4-26, Energy usage (kWh/ m^2-yr) across orientations for solar radiation control strategies in Minneapolis with window D, SHGC=0.28/ U=1.61/ Tvis=0.64, two shade colors and WWR of 0.40.

North	NS	*WS_189_ctr*	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
Heating	114.85	124.39	124.21	124.02	124.12	124.10	124.11
Cooling	16.39	12.81	12.87	12.99	12.96	12.92	13.00
Lighting	30.34	5.68	5.46	5.46	5.76	5.46	5.47
Total	161.58	142.89	142.53	142.47	142.84	142.49	142.57
South							
Heating	87.14	102.43	101.86	94.04	91.04	92.79	94.11
Cooling	21.04	15.85	15.93	17.63	19.85	18.78	17.65
Lighting	30.34	12.13	8.04	8.03	18.94	13.11	8.03
Total	138.52	130.41	125.83	119.70	129.83	124.68	119.79
East							
Heating	104.86	116.62	116.08	113.82	111.75	112.97	113.90
Cooling	21.18	15.65	15.88	17.85	18.89	18.39	17.86
Lighting	30.33	6.54	4.85	5.70	11.58	8.30	5.70
Total	156.37	138.81	136.81	137.37	142.23	139.66	137.47
West							
Heating	106.46	116.43	116.07	114.40	112.73	113.83	114.48
Cooling	20.47	15.90	15.98	17.59	19.16	18.48	17.60
Lighting	30.33	10.76	8.21	8.18	14.76	11.16	8.19
Total	157.27	143.08	140.25	140.17	146.65	143.47	140.28

Table A-19: Results for figure 4-25, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Philadelphia, Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	NS	*WS_189_ctr*	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
Heating	83.52	77.08	76.97	76.81	76.90	76.87	76.78
Cooling	23.89	21.69	21.79	21.93	21.95	21.85	21.95
Lighting	30.34	5.97	5.69	5.69	6.10	5.69	5.69
Total	137.74	104.74	104.45	104.43	104.95	104.41	104.42
South							
Heating	59.45	57.97	57.58	55.53	48.31	49.92	51.49
Cooling	28.19	25.42	25.63	26.67	30.46	28.93	27.61
Lighting	30.34	12.36	8.18	6.19	18.92	12.94	8.05
Total	117.98	95.75	91.39	88.39	97.69	91.79	87.16
East							
Heating	73.11	69.34	68.93	67.21	64.39	65.52	66.65
Cooling	28.61	25.00	25.40	26.43	28.71	28.15	27.61
Lighting	30.33	7.12	5.66	5.50	11.58	8.73	6.37
Total	132.05	101.46	99.99	99.15	104.68	102.39	100.63
West							
Heating	75.56	69.78	69.63	68.57	66.43	67.53	68.19
Cooling	28.43	25.74	25.81	26.73	30.14	29.03	27.73
Lighting	30.33	10.90	8.00	6.75	15.19	11.08	7.61
Total	134.32	106.41	103.44	102.05	111.76	107.64	103.52

Table A-20: Results for figure 4-27, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Seattle with Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	NS	*WS_189_ctr*	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
Heating	54.33	63.65	63.53	63.39	63.45	63.43	63.37
Cooling	13.24	8.95	9.00	9.09	9.12	9.07	9.11
Lighting	30.24	6.66	6.46	6.46	6.72	6.46	6.46
Total	97.82	79.26	78.99	78.94	79.29	78.96	78.94
South							
Heating	44.99	54.68	54.33	53.27	51.12	52.42	52.71
Cooling	18.25	12.58	12.57	13.31	16.57	15.32	14.13
Lighting	30.24	13.38	9.41	7.67	17.16	11.81	8.39
Total	93.48	80.64	76.31	74.25	84.86	79.55	75.22
East							
Heating	50.72	60.85	60.55	60.13	58.99	59.81	60.02
Cooling	16.73	10.89	11.10	11.69	13.44	12.85	12.41
Lighting	30.24	7.23	5.74	5.60	10.19	7.49	6.09
Total	97.69	78.97	77.39	77.42	82.62	80.15	78.52
West							
Heating	50.84	58.83	58.59	58.01	57.52	58.04	57.92
Cooling	17.89	12.72	12.69	13.06	16.11	15.26	14.41
Lighting	30.24	12.39	10.04	9.18	15.11	11.96	10.17
Total	98.96	83.94	81.33	80.25	88.74	85.26	82.51

Table A-21: Results for table 4-18 and 4-28, Energy usage (kWh/ m^2-yr) across orientations for solar radiation control strategies in Phoenix with window D, SHGC=0.28/ U=1.61/ Tvis=0.64, two shade colors and WWR of 0.40.

North	*NS*	*WS_189_ctr*	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
Heating	5.81	8.08	8.03	7.97	7.99	7.98	7.94
Cooling	63.27	56.67	56.74	56.99	57.37	56.91	57.08
Lighting	30.34	5.30	4.37	4.37	5.72	4.37	4.37
Total	99.42	70.05	69.13	69.32	71.09	69.25	69.38
South							
Heating	1.74	4.03	3.99	3.80	3.24	3.36	3.48
Cooling	79.09	68.39	68.47	70.44	80.07	77.50	75.49
Lighting	30.34	12.37	7.26	4.87	20.93	13.89	8.42
Total	111.16	84.79	79.73	79.11	104.24	94.75	87.39
East							
Heating	3.65	5.70	5.68	5.36	4.78	5.01	5.28
Cooling	76.97	65.64	66.08	68.11	74.28	73.35	72.14
Lighting	30.33	5.91	4.28	3.98	12.80	9.83	6.37
Total	110.95	77.25	76.04	77.45	91.85	88.19	83.79
West							
Heating	4.21	6.58	6.47	6.10	6.17	6.17	6.03
Cooling	76.31	67.02	67.01	68.30	75.98	74.60	72.47
Lighting	30.33	9.32	6.74	5.07	15.89	12.37	8.03
Total	110.85	82.92	80.22	79.48	98.05	93.14	86.53

Table A-22: Results for figure 4-27, Energy usage (kWh/ m^2-yr) across orientations and different control strategies for Houston with Window D, SHGC=0.27/ U=0.26/ Tvis=0.64, two shade colors and WWR of 0.40.

North	*NS*	*WS_189_ctr*	*WS_378_ctr*	*WS_630_ctr*	*DS_189_ctr*	*DS_378_ctr*	*DS_630_ctr*
Heating	10.33	12.6	12.56	12.51	12.54	12.53	12.5
Cooling	50.12	42.18	42.28	42.46	42.5	42.36	42.48
Lighting	30.34	4.38	4	4	4.55	4	4
Total	90.79	59.15	58.84	58.96	59.6	58.89	58.97
South							
Heating	6.43	8.66	8.61	8.27	7.26	7.59	7.76
Cooling	58.74	48.47	48.65	49.78	55.57	52.98	51.69
Lighting	30.34	11.46	6.29	4.93	17.26	9.94	6.54
Total	95.52	68.6	63.55	62.98	80.09	70.52	65.99
East							
Heating	8.23	10.57	10.54	10.18	9.45	9.75	10.1
Cooling	57.58	46.73	47.21	48.79	52.29	51.05	49.89
Lighting	30.33	5.44	3.58	3.4	10.92	7.2	4.14
Total	96.14	62.74	61.32	62.37	72.65	68	64.14
West							
Heating	8.88	10.99	10.93	10.61	10.51	10.6	10.57
Cooling	57.71	48.5	48.63	49.59	54.29	52.75	50.99
Lighting	30.33	9.6	6.85	5.64	14.17	10.18	6.72
Total	96.93	69.09	66.41	65.84	78.96	73.53	68.28

Appendix B

Detailed results for chapter 5

Table B-1: The lighting energy use (kWh) for clear and overcast days in Minneapolis on March 21 and Mar 25 for a west-facing private office with occupancy from 7am to 7pm DST and white shades (Table 5-5).

White shade

Clear	21-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.133	0.119	0.119	0.119	0.119
	8:00	0.135	0.126	0.075	0.075	0.075	0.075
	9:00	0.135	0.121	0.049	0.049	0.049	0.049
	10:00	0.135	0.116	0.029	0.029	0.029	0.029
	11:00	0.135	0.113	0.006	0.006	0.006	0.006
	12:00	0.135	0.110	0.000	0.000	0.000	0.000
	13:00	0.135	0.100	0.000	0.000	0.000	0.000
	14:00	0.135	0.057	0.000	0.000	0.000	0.000
	15:00	0.135	0.003	0.000	0.003	0.000	0.003
	16:00	0.135	0.000	0.000	0.000	0.000	0.000
	17:00	0.135	0.000	0.000	0.000	0.000	0.000
	18:00	0.135	0.019	0.019	0.019	0.019	0.019
		1.621	0.899	0.297	0.300	0.297	0.300
			44.54%	81.70%	81.50%	81.70%	81.50%
	25-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.133	0.117	0.117	0.117	0.117
	8:00	0.135	0.125	0.058	0.058	0.058	0.058
	9:00	0.135	0.119	0.016	0.016	0.016	0.016
	10:00	0.135	0.115	0.000	0.000	0.000	0.000
	11:00	0.135	0.113	0.000	0.000	0.000	0.000
	12:00	0.135	0.100	0.000	0.000	0.000	0.000
	13:00	0.135	0.101	0.000	0.000	0.000	0.000
	14:00	0.135	0.066	0.000	0.000	0.000	0.000
	15:00	0.135	0.088	0.000	0.088	0.000	0.000
	16:00	0.135	0.091	0.091	0.091	0.000	0.000
	17:00	0.135	0.112	0.112	0.000	0.112	0.112
	18:00	0.135	0.129	0.129	0.129	0.079177	0.079
		1.621	1.290	0.523	0.498	0.382	0.382
			20.43%	67.77%	69.26%	76.43%	76.43%

Table B-2: The lighting energy use (kWh) for clear and overcast days in Minneapolis on March 21 and Mar 25 for a west-facing private office with occupancy from 7am to 7pm DST and dark shades (Table 5-5).

Dark shade

Clear	21-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.135	0.119	0.119	0.119	0.119
	8:00	0.135	0.133	0.075	0.075	0.075	0.075
	9:00	0.135	0.131	0.048	0.049	0.049	0.049
	10:00	0.135	0.130	0.028	0.029	0.029	0.029
	11:00	0.135	0.129	0.005	0.006	0.006	0.006
	12:00	0.135	0.128	0.000	0.000	0.000	0.000
	13:00	0.135	0.125	0.000	0.000	0.000	0.000
	14:00	0.135	0.113	0.000	0.000	0.000	0.000
	15:00	0.135	0.095	0.100	0.101	0.101	0.101
	16:00	0.135	0.083	0.090	0.090	0.090	0.090
	17:00	0.135	0.083	0.089	0.090	0.090	0.090
	18:00	0.135	0.095	0.100	0.100	0.100	0.100
		1.621	1.380	0.654	0.658	0.658	0.658
			14.90%	59.67%	59.39%	59.39%	59.39%
	25-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.134	0.117	0.117	0.117	0.117
	8:00	0.135	0.132	0.057	0.058	0.058	0.058
	9:00	0.135	0.131	0.015	0.016	0.016	0.016
	10:00	0.135	0.129	0.000	0.000	0.000	0.000
	11:00	0.135	0.129	0.000	0.000	0.000	0.000
	12:00	0.135	0.125	0.000	0.000	0.000	0.000
	13:00	0.135	0.125	0.000	0.000	0.000	0.000
	14:00	0.135	0.116	0.000	0.000	0.000	0.000
	15:00	0.135	0.122	0.123	0.123	0.000	0.000
	16:00	0.135	0.123	0.124	0.124	0.124	0.124
	17:00	0.135	0.129	0.129	0.000	0.000	0.000
	18:00	0.135	0.133	0.134	0.134	0.134	0.079
		1.621	1.528	0.700	0.572	0.449	0.394
			5.76%	56.81%	64.70%	72.32%	75.67%

Table B-3: The lighting energy use (kWh) for clear and overcast days in Minneapolis on March 21 and Mar 25 for a south-facing private office with occupancy from 7am to 7pm DST and white shades (Table 5-6).

White shade

Clear	21-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.132	0.116	0.116	0.116	0.116
	8:00	0.135	0.111	0.111	0.111	0.111	0.034
	9:00	0.135	0.064	0.064	0.064	0.064	0.000
	10:00	0.135	0.009	0.009	0.009	0.009	0.000
	11:00	0.135	0.000	0.000	0.000	0.000	0.000
	12:00	0.135	0.000	0.000	0.000	0.000	0.000
	13:00	0.135	0.000	0.000	0.000	0.000	0.000
	14:00	0.135	0.000	0.000	0.000	0.000	0.000
	15:00	0.135	0.000	0.000	0.000	0.000	0.000
	16:00	0.135	0.031	0.031	0.031	0.031	0.000
	17:00	0.135	0.087	0.000	0.000	0.000	0.000
	18:00	0.135	0.123	0.070	0.070	0.070	0.070
		1.621	0.556	0.400	0.400	0.400	0.220
			65.70%	75.31%	75.31%	75.31%	86.43%
	25-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.132	0.110	0.110	0.110	0.110
	8:00	0.135	0.119	0.119	0.119	0.019	0.019
	9:00	0.135	0.100	0.100	0.100	0.100	0.000
	10:00	0.135	0.074	0.074	0.074	0.074	0.000
	11:00	0.135	0.066	0.066	0.066	0.066	0.000
	12:00	0.135	0.013	0.013	0.013	0.013	0.013
	13:00	0.135	0.063	0.063	0.000	0.000	0.063
	14:00	0.135	0.014	0.014	0.014	0.014	0.014
	15:00	0.135	0.086	0.086	0.086	0.000	0.000
	16:00	0.135	0.104	0.104	0.104	0.104	0.000
	17:00	0.135	0.118	0.010	0.010	0.010	0.010
	18:00	0.135	0.130	0.094	0.094	0.094	0.094
		1.621	1.018	0.852	0.789	0.603	0.322
			37.22%	47.47%	51.35%	62.81%	80.12%

Table B-4: The lighting energy use (kWh) for clear and overcast days in Minneapolis on March 21 and Mar 25 for a south-facing private office with occupancy from 7am to 7pm DST and dark shades (Table 5-6).

Dark shade

Clear	21-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.134	0.116	0.116	0.116	0.116
	8:00	0.135	0.129	0.129	0.129	0.129	0.034
	9:00	0.135	0.118	0.118	0.118	0.118	0.000
	10:00	0.135	0.104	0.104	0.104	0.104	0.000
	11:00	0.135	0.094	0.094	0.094	0.094	0.094
	12:00	0.135	0.089	0.089	0.089	0.089	0.089
	13:00	0.135	0.087	0.087	0.087	0.087	0.087
	14:00	0.135	0.091	0.091	0.091	0.091	0.091
	15:00	0.135	0.098	0.098	0.098	0.098	0.098
	16:00	0.135	0.110	0.110	0.110	0.110	0.000
	17:00	0.135	0.123	0.000	0.000	0.000	0.000
	18:00	0.135	0.132	0.070	0.070	0.070	0.070
		1.621	1.310	1.106	1.106	1.106	0.679
			19.19%	31.77%	31.77%	31.77%	58.10%
	25-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.134	0.110	0.110	0.110	0.110
	8:00	0.135	0.131	0.131	0.131	0.131	0.019
	9:00	0.135	0.127	0.127	0.127	0.127	0.000
	10:00	0.135	0.120	0.120	0.120	0.120	0.000
	11:00	0.135	0.118	0.118	0.118	0.118	0.000
	12:00	0.135	0.105	0.105	0.105	0.105	0.105
	13:00	0.135	0.117	0.117	0.000	0.117	0.117
	14:00	0.135	0.105	0.105	0.105	0.105	0.105
	15:00	0.135	0.123	0.123	0.123	0.123	0.000
	16:00	0.135	0.127	0.127	0.127	0.127	0.000
	17:00	0.135	0.131	0.010	0.010	0.010	0.010
	18:00	0.135	0.134	0.094	0.094	0.094	0.094
		1.621	1.473	1.288	1.170	1.288	0.560
			9.14%	20.58%	27.82%	20.58%	65.45%

Table B-5: The lighting energy use (kWh) for clear and overcast days in Phoenix on March 28 and Mar 20 for a west-facing private office with occupancy from 7am to 7pm DST and white shades (Table 5-7).

White shade

Clear	28-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.135	0.135	0.118	0.135	0.118
	8:00	0.135	0.132	0.115	0.062	0.115	0.062
	9:00	0.135	0.123	0.052	0.022	0.052	0.022
	10:00	0.135	0.114	0.007	0.000	0.007	0.000
	11:00	0.135	0.107	0.000	0.000	0.000	0.000
	12:00	0.135	0.099	0.000	0.000	0.000	0.000
	13:00	0.135	0.090	0.000	0.000	0.000	0.000
	14:00	0.135	0.086	0.086	0.058	0.086	0.058
	15:00	0.135	0.044	0.044	0.007	0.044	0.007
	16:00	0.135	0.000	0.000	0.000	0.000	0.000
	17:00	0.135	0.000	0.000	0.000	0.000	0.000
	18:00	0.135	0.000	0.000	0.012	0.000	0.012
		1.621	0.932	0.439	0.278	0.439	0.278
			42.52%	72.93%	82.83%	72.93%	82.83%
	20-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.135	0.135	0.130	0.135	0.118
	8:00	0.135	0.134	0.129	0.100	0.129	0.062
	9:00	0.135	0.130	0.095	0.035	0.095	0.022
	10:00	0.135	0.119	0.024	0.000	0.024	0.000
	11:00	0.135	0.108	0.000	0.000	0.000	0.000
	12:00	0.135	0.100	0.000	0.000	0.000	0.000
	13:00	0.135	0.092	0.000	0.000	0.000	0.000
	14:00	0.135	0.082	0.082	0.000	0.000	0.000
	15:00	0.135	0.070	0.070	0.067	0.000	0.007
	16:00	0.135	0.056	0.056	0.059	0.056	0.000
	17:00	0.135	0.046	0.046	0.021	0.046	0.000
	18:00	0.135	0.009	0.009	0.098	0.000	0.012
		1.621	1.080	0.645	0.510	0.485	0.220
			33.37%	60.22%	68.54%	70.10%	86.44%

Table B-6: The lighting energy use (kWh) for clear and overcast days in Phoenix on March 28 and Mar 20 for a west-facing private office with occupancy from 7am to 7pm DST and dark shades (Table 5-7).

Dark shade

Clear	28-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.135	0.135	0.118	0.135	0.118
	8:00	0.135	0.134	0.115	0.062	0.115	0.062
	9:00	0.135	0.132	0.052	0.022	0.052	0.022
	10:00	0.135	0.130	0.007	0.000	0.007	0.000
	11:00	0.135	0.128	0.000	0.000	0.000	0.000
	12:00	0.135	0.127	0.000	0.000	0.000	0.000
	13:00	0.135	0.124	0.000	0.000	0.000	0.000
	14:00	0.135	0.123	0.123	0.116	0.123	0.000
	15:00	0.135	0.113	0.113	0.102	0.113	0.102
	16:00	0.135	0.097	0.097	0.090	0.097	0.090
	17:00	0.135	0.084	0.084	0.087	0.084	0.087
	18:00	0.135	0.080	0.080	0.098	0.080	0.098
		1.621	1.408	0.806	0.695	0.806	0.578
			13.13%	50.28%	57.15%	50.28%	64.32%
	20-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.135	0.135	0.130	0.135	0.130
	8:00	0.135	0.135	0.129	0.100	0.129	0.100
	9:00	0.135	0.134	0.095	0.035	0.095	0.035
	10:00	0.135	0.131	0.024	0.000	0.024	0.000
	11:00	0.135	0.129	0.000	0.000	0.000	0.000
	12:00	0.135	0.127	0.000	0.000	0.000	0.000
	13:00	0.135	0.125	0.000	0.000	0.000	0.000
	14:00	0.135	0.122	0.122	0.000	0.000	0.000
	15:00	0.135	0.119	0.119	0.119	0.000	0.119
	16:00	0.135	0.116	0.116	0.116	0.116	0.116
	17:00	0.135	0.114	0.114	0.107	0.114	0.107
	18:00	0.135	0.103	0.103	0.126	0.000	0.126
		1.621	1.490	0.958	0.733	0.613	0.733
			8.11%	40.92%	54.76%	62.20%	54.76%

Table B-7: The lighting energy use (kWh) for clear and overcast days in Phoenix on March 28 and Mar 20 for a south-facing private office with occupancy from 7am to 7pm DST and white shades (Table 5-8).

White shade

Clear	28-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.135	0.135	0.135	0.135	0.135
	8:00	0.135	0.132	0.114	0.114	0.114	0.114
	9:00	0.135	0.115	0.032	0.032	0.032	0.032
	10:00	0.135	0.084	0.084	0.084	0.084	0.000
	11:00	0.135	0.042	0.042	0.042	0.042	0.042
	12:00	0.135	0.003	0.003	0.003	0.003	0.003
	13:00	0.135	0.000	0.000	0.000	0.000	0.000
	14:00	0.135	0.000	0.000	0.000	0.000	0.000
	15:00	0.135	0.000	0.000	0.000	0.000	0.000
	16:00	0.135	0.006	0.006	0.006	0.006	0.000
	17:00	0.135	0.044	0.044	0.044	0.044	0.000
	18:00	0.135	0.086	0.000	0.000	0.000	0.000
		1.621	0.647	0.460	0.460	0.460	0.326
			60.11%	71.65%	71.65%	71.65%	79.91%
	20-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.135	0.135	0.135	0.135	0.135
	8:00	0.135	0.134	0.128	0.128	0.128	0.128
	9:00	0.135	0.129	0.087	0.087	0.087	0.087
	10:00	0.135	0.112	0.112	0.004	0.004	0.004
	11:00	0.135	0.088	0.088	0.000	0.000	0.000
	12:00	0.135	0.073	0.073	0.000	0.000	0.073
	13:00	0.135	0.064	0.064	0.000	0.000	0.064
	14:00	0.135	0.057	0.057	0.000	0.000	0.057
	15:00	0.135	0.055	0.055	0.000	0.000	0.055
	16:00	0.135	0.057	0.057	0.057	0.000	0.000
	17:00	0.135	0.075	0.075	0.075	0.075	0.000
	18:00	0.135	0.085	0.000	0.000	0.000	0.000
		1.621	1.064	0.932	0.487	0.429	0.605
			34.35%	42.51%	69.96%	73.52%	62.69%

Table B-8: The lighting energy use (kWh) for clear and overcast days in Phoenix on March 28 and Mar 20 for a south-facing private office with occupancy from 7am to 7pm DST and dark shades (Table 5-8).

Dark shade

Clear	28-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
	7:00	0.135	0.135	0.135	0.135	0.135	0.135
	8:00	0.135	0.134	0.114	0.114	0.114	0.114
	9:00	0.135	0.130	0.032	0.032	0.032	0.032
	10:00	0.135	0.123	0.123	0.123	0.123	0.000
	11:00	0.135	0.113	0.113	0.113	0.113	0.113
	12:00	0.135	0.103	0.103	0.103	0.103	0.103
	13:00	0.135	0.095	0.095	0.095	0.095	0.095
	14:00	0.135	0.094	0.094	0.094	0.094	0.094
	15:00	0.135	0.097	0.097	0.097	0.097	0.097
	16:00	0.135	0.104	0.104	0.104	0.104	0.000
	17:00	0.135	0.113	0.113	0.113	0.113	0.000
	18:00	0.135	0.123	0.000	0.000	0.000	0.000
		1.621	1.365	1.123	1.123	1.123	0.783
			15.82%	30.75%	30.75%	30.75%	51.72%
	20-Mar	*NS*	*DN_ctr*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
Overcast	7:00	0.135	0.135	0.135	0.135	0.135	0.135
	8:00	0.135	0.135	0.128	0.128	0.128	0.128
	9:00	0.135	0.134	0.087	0.087	0.087	0.087
	10:00	0.135	0.130	0.130	0.004	0.004	0.004
	11:00	0.135	0.124	0.124	0.000	0.000	0.000
	12:00	0.135	0.120	0.120	0.000	0.000	0.120
	13:00	0.135	0.118	0.118	0.000	0.000	0.118
	14:00	0.135	0.116	0.116	0.000	0.000	0.116
	15:00	0.135	0.116	0.116	0.000	0.000	0.116
	16:00	0.135	0.116	0.116	0.116	0.000	0.000
	17:00	0.135	0.121	0.121	0.000	0.121	0.000
	18:00	0.135	0.123	0.000	0.000	0.000	0.000
		1.621	1.487	1.311	0.471	0.475	0.825
			8.26%	19.13%	70.94%	70.68%	49.09%

Table B-9: The annual lighting energy use (kWh/m^2-yr) for west-facing windows under the different control strategies across all cities (Figure 5-4).

kWh/m^2-yr	Philadelphia	Minneapolis	Seattle	Houston	Phoenix
NS	30.33	30.33	30.24	30.33	30.33
DN_WS_ctr	22.22	23.55	24.48	24.75	24.75
WS_ApAz_ctr	12.25	11.37	12.94	10.41	9.26
WS_DIR 2500_ctr	10.25	10.58	11.26	9.20	8.89
WS_DIR5000_ctr	10.14	9.98	11.07	8.99	8.70
WS_Ewp_ctr	9.11	9.07	9.92	8.34	7.25
DN_DS_ctr	28.64	28.68	28.84	28.97	28.97
DS_ApAz_ctr	15.92	16.02	16.89	15.60	17.23
DS_DIR 2500_ctr	13.40	14.35	13.68	12.81	15.66
DS_DIR5000_ctr	14.07	14.09	14.38	13.67	16.56
DS_Ewp _ctr	12.16	12.79	12.18	11.91	12.68

Table B-10: The annual lighting energy use (kWh/m^2-yr) for south-facing windows under the different control strategies across all cities (Figure 5-5).

kWh/m^2-yr	Philadelphia	Minneapolis	Seattle	Houston	Phoenix
NS	30.34	30.34	30.24	30.34	30.34
DN_WS_ctr	19.89	20.94	23.34	21.77	23.90
WS_ApAz_ctr	14.01	15.21	12.50	10.52	18.43
WS_DIR 2500_ctr	10.78	12.17	9.62	9.54	12.76
WS_DIR5000_ctr	10.78	11.62	9.62	9.48	12.76
WS_Ewp_ctr	8.56	9.07	7.77	7.46	9.99
DN_DS_ctr	28.13	28.04	28.56	28.25	28.77
DS_ApAz_ctr	21.13	24.60	18.43	18.46	23.23
DS_DIR 2500_ctr	17.01	19.28	14.67	16.88	17.38
DS_DIR5000_ctr	17.45	18.01	14.96	17.32	18.97
DS_Ewp_ctr	13.52	14.29	11.60	12.97	13.41

Table B-11: Heating, cooling, lighting and total energy use (kWh/m^2-yr) for static and dynamic shade control strategies in Minneapolis on a west-facing private office with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades (Table 5-9).

West	*NS*	*DN _WS*	*DN _WS_ctr*	*EMWA _WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ ApAz_ctr*	*WS_DIR 2500_ctr*	*WS_DIR 5000_ctr*	*WS_ Ewp_ctr*
Heating	106.46	108.52	109.63	114.29	116.43	116.07	114.4	109.33	110.39	109.51	109.16
Cooling	20.47	18.56	16.96	16.45	15.9	15.98	17.59	18.79	17.72	18.79	17.72
Lighting	30.33	30.33	23.55	13.48	10.76	8.21	8.18	10.47	9.73	9.18	8.63
Total	157.27	157.42	150.15	144.23	143.08	140.25	140.17	138.59	137.84	137.48	135.51

West	*NS*	*DN _DS*	*DN _DS_ctr*	*EMWA _DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ ApAz_ctr*	*DS_DIR 2500_ctr*	*DS_DIR 5000_ctr*	*DS_ Ewp_ctr*
Heating	106.46	104.47	104.91	110.78	112.73	113.83	114.48	110.08	110.82	110.82	111.92
Cooling	20.47	21.75	21.42	19.71	19.16	18.48	17.6	20.17	20.01	19.96	20.07
Lighting	30.33	30.33	28.68	17.99	14.76	11.16	8.19	14.69	13.22	13.04	11.75
Total	157.27	156.56	155.01	148.48	146.65	143.47	140.28	144.95	144.06	143.82	143.74

Table B-12: Heating, cooling, lighting and total energy use (kWh/m^2-yr) for static and dynamic shade control strategies in Minneapolis on a south-facing private office with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white shades (Table 5-10).

South	*NS*	*DN _WS*	*DN _WS_ctr*	*EMWA _WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ ApAz_ctr*	*WS_DIR 2500_ctr*	*WS_DIR 5000_ctr*	*WS_ Ewp_ctr*
Heating	87.14	92.72	95.83	96.94	102.43	101.86	94.04	93.01	93.01	87.57	91.43
Cooling	21.04	18.61	16.85	16.98	15.85	15.93	17.63	17.76	17.87	18.37	18.32
Lighting	30.34	30.34	20.94	19.55	12.13	8.04	8.03	14.33	11.20	11.75	8.45
Total	138.52	141.67	133.63	133.47	130.41	125.83	119.7	125.10	122.08	117.70	118.20

South	*NS*	*DN _DS*	*DN _DS_ctr*	*EMWA _DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ ApAz_ctr*	*DS_DIR 2500_ctr*	*DS_DIR 5000_ctr*	*DS_ Ewp_ctr*
Heating	87.14	84.78	85.6	85.86	91.04	92.79	94.11	85.60	87.95	87.95	89.90
Cooling	21.04	21.96	21.58	21.5	19.85	18.78	17.65	20.58	20.22	20.07	19.65
Lighting	30.34	30.34	28.04	27.64	18.94	13.11	8.03	21.86	17.82	16.53	13.22
Total	138.52	137.08	135.22	135	129.83	124.68	119.79	128.04	125.98	124.54	122.78

Table B-13: Heating, cooling, lighting and total energy use (kWh/m^2-yr) for static and dynamic shade control strategies in Phoenix on a west-facing private office with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white and dark shades (Table 5-11).

West	*NS*	*DN _WS*	*DN _WS_ctr*	*EMWA _WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ ApAz_ctr*	*WS_DIR 2500_ctr*	*WS_DIR 5000_ctr*	*WS_ Ewp_ctr*
Heating	4.21	4.73	4.85	6.24	6.58	6.47	6.1	4.74	4.74	4.74	4.48
Cooling	76.31	66.03	64.1	68.14	67.02	67.01	68.3	65.33	65.33	65.33	65.88
Lighting	30.33	30.33	24.75	9.3	9.32	6.74	5.07	8.45	8.27	8.08	6.61
Total	110.85	101.09	93.7	83.67	82.92	80.22	79.48	78.52	78.34	78.15	76.96

West	*NS*	*DN _DS*	*DN _DS_ctr*	*EMWA _DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ ApAz_ctr*	*DS_DIR 2500_ctr*	*DS_DIR 5000_ctr*	*DS_ Ewp_ctr*
Heating	4.21	4.57	4.59	6.04	6.17	6.17	6.03	5.04	5.04	5.04	5.04
Cooling	76.31	69.8	69.32	76.33	75.98	74.6	72.47	66.59	67.84	66.38	66.94
Lighting	30.33	30.33	28.97	15.76	15.89	12.37	8.03	15.80	14.51	15.24	11.75
Total	110.85	104.7	102.89	98.14	98.05	93.14	86.53	87.43	87.40	86.67	83.73

Table B-14: Heating, cooling, lighting and total energy use (kWh/m^2-yr) for static and dynamic shade control strategies in Phoenix on a south-facing private office with window D (SHGC=0.28/ U=1.61/ Tvis=0.64), WWR=0.40 and white shades (Table 5-12).

South	*NS*	*DN _WS*	*DN _WS_ctr*	*EMWA _WS _ctr*	*WS_189 _ctr*	*WS_378 _ctr*	*WS_630 _ctr*	*WS_ ApAz_ctr*	*WS_DIR 2500_ctr*	*WS_DIR 5000_ctr*	*WS_ Ewp_ctr*
Heating	1.74	3.06	3.29	3.45	4.03	3.99	3.8	3.03	2.89	2.89	2.61
Cooling	79.09	66.84	64.62	71.03	68.39	68.47	70.44	67.71	68.47	67.91	71.61
Lighting	30.34	30.34	23.9	17.7	12.37	7.26	4.87	8.63	7.90	7.90	6.24
Total	111.16	100.24	91.81	92.18	84.79	79.73	79.11	79.37	79.26	78.70	80.47

South	*NS*	*DN _DS*	*DN _DS_ctr*	*EMWA _DS _ctr*	*DS_189 _ctr*	*DS_378 _ctr*	*DS_630 _ctr*	*DS_ ApAz_ctr*	*DS_DIR 2500_ctr*	*DS_DIR 5000_ctr*	*DS_ Ewp_ctr*
Heating	1.74	2.81	2.84	2.99	3.24	3.36	3.48	2.80	2.80	2.80	3.02
Cooling	79.09	71	70.44	83.2	80.07	77.5	75.49	67.32	66.98	67.11	66.02
Lighting	30.34	30.34	28.77	27.14	20.93	13.89	8.42	17.08	15.61	15.98	11.94
Total	111.16	104.15	102.06	113.32	104.24	94.75	87.39	87.20	85.39	85.89	80.98

Table B-15: The useful daylight illuminance range (UDI) for west-facing offices in Minneapolis with a white shade (*WS*) (table 5-13).

Control strategies	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	500	2112	843	699	637	526
100<UDI<2000	3309	2613	3772	3927	3949	4186
UDI>2000	883	0	77	102/4927	106	16

Table B-16: The useful daylight illuminance range (UDI) for south-facing offices in Minneapolis with a white shade (*WS*) (table 5-14).

Control strategies	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	598	1667	910	771	749	598
100<UDI<2000	2811	3059	3810	3850	3863	4128
UDI>2000	1319	2	8	107	116	2

Table B-17: The useful daylight illuminance range (UDI) for west-facing offices in Minneapolis with a dark shade (*DS*) (table 5-15).

Control strategies	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	500	3927	1526	1196	1125	832
100<UDI<2000	3309	799	3119	3431	3497	3880
UDI>2000	883	0	85	99	109	14

Table B-18: The useful daylight illuminance range (UDI) for south-facing offices in Minneapolis with a dark shade (*DS*) (table 5-16).

Control strategies	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
UDI<100	598	3700	2452	1767	1802	983
100<UDI<2000	2811	1027	2272	2961	2924	3744
UDI>2000	1319	0	2	0	0	0

Table B-19: The Daylight Glare Index (DGI) range for west-facing offices in Minneapolis with a white shade (WS) (table 5-17).

DGI range	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	2411	4366	3452	3250	3176	3110
22<DGI≤24	1031	8	721	773	784	905
DGI>24	1283	0	553	703	758	711

Table B-20: The Daylight Glare Index (DGI) range for south-facing offices in Minneapolis with a white shade (WS) (table 5-18).

DGI range	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	2079	4257	4082	3546	3518	3178
22<DGI≤24	816	107	412	499	505	759
DGI>24	1830	0	232	681	703	789

Table B-21: The Daylight Glare Index (DGI) range for west-facing offices in Minneapolis with a dark shade (DS) (table 5-19).

DGI range	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	2411	3107	3300	3131	3095	3117
22<DGI≤24	1031	0	705	767	776	898
DGI>24	1283	0	721	828	855	711

Table B-22: The Daylight Glare Index (DGI) range for south-facing offices in Minneapolis with a dark shade (DS) (table 5-20).

DGI range	*NS*	*DN*	*ApAz_ctr*	*DIR 2500_ctr*	*DIR 5000_ctr*	*Ewp_ctr*
DGI≤22	2079	3490	4072	3497	3322	3284
22<DGI≤24	816	0	282	393	469	653
DGI>24	1830	0	372	836	935	789

Table B-23: The number of view hours under the different control strategies for west and south-facing windows in the five test cities.

Cities	Control type	South (hours)	West (hours)
Philadelphia	*Ap_Az_ctr*	2,561	1,711
	DIR 2500_ctr	1,806	1,346
	DIR 5000_ctr	1,883	1,290
	Ewp_ctr	1,162	880
Minneapolis	*Ap_Az_ctr*	2,954	1,721
	DIR 2500_ctr	2,297	1,371
	DIR 5000_ctr	2,243	1,296
	Ewp_ctr	1,318	882
Seattle	*Ap_Az_ctr*	2,954	1,717
	DIR 2500_ctr	1,816	1,304
	DIR 5000_ctr	1,926	1,218
	Ewp_ctr	955	754
Houston	*Ap_Az_ctr*	2,160	1,774
	DIR 2500_ctr	1,487	1,408
	DIR 5000_ctr	1,538	1,331
	Ewp_ctr	893	1,045
Phoenix	*Ap_Az_ctr*	2,293	1,826
	DIR 2500_ctr	2,020	1,753
	DIR 5000_ctr	2,067	1,711
	Ewp_ctr	1,240	1,243

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