PERFORMANCE ANALYSIS OF PHOTOCONTROL SYSTEMS
ACROSS SHADE SETTINGS

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ABSTRACT

Daylight-responsive photocontrol systems have been commercially available for over two decades. Technological advancements have improved the performance and decreased the cost of these systems. Implementing daylight responsive photocontrol systems has been recognized as good design practice for energy-efficient buildings and are now promoted by energy codes, but a combination of dynamic daylighting conditions and control device operation makes the prediction of the system performance difficult to assess. Past research reveals that reliable photocontrol system operation requires proper configuration, such as the sensor aiming direction, the directional sensitivity (type), and the position of the photosensor, as well as proper system calibration. Most past studies were conducted assuming no shades or a fixed shade position. Few studies have explored the impact of window shading on system performance.

Recent developments in daylight simulations have introduced Bidirectional Scattering Distribution Functions (BSDF) that improve the accuracy of simulation results for complex fenestration systems, provide more accurate simulations of the direct sun, and apply matrix-based simulation methods, which allow the reuse of the calculated matrices and provide efficient simulations for parametric modeling. Taking advantage of these developments, this study focuses on the evaluation of photocontrol system performance across different shade settings. The signal to work plane illuminance (S/E) ratios are assumed to be constant in most linearly controlled systems. The S/E ratio was employed as a key response measure in this study.

Statistical analysis procedures are introduced to explore the significance of the independent variables - environmental variables and system configurations. ANOVA models fitted for the system performance across shade settings in this study explain about 90% of the response variance. The results show that shade setting is one of the most important factors in photocontrol system performance. A clear sky condition has been considered the primary cause of large response variations in system with a fixed shade setting, but, in systems integrated with multiple shade settings, the variance in S/E ratios introduced by the sky conditions is shown to be not as significant as that due to the shade operation. When window shades were lowered to a fixed position, the variance of S/E ratios in a system with low angle exterior obstructions was higher than that in a system without exterior obstructions, but the impact of the obstruction was comparably weak in a system with dynamically controlled shade.
A number of system configuration variables were major contributors to the system performance when taking the shade settings into account. The aiming direction of the photosensor was ranked highest in importance. Directing the photosensor away from the window delivered high quality system performance. A photosensor located at a mid-depth (daylight zone) 7 ft (2.1 m) achieved better response accuracy over a photosensor located closer to the window and received higher signal than a deeper photosensor position, which delivered similar performance to the mid-depth photosensor. The directional sensitivity of the photosensor has a relevant weak contribution to the photocontrol system performance. A mid-depth cosine-corrected photosensor is generally preferred. In a study with LightLouver™ specular sunlight redirection system, the conclusions for the aiming direction and the depth of the photosensor are similar, but a photosensor with a narrower distribution generally delivers better performance.

Energy performance case studies with an automated shading strategy were conducted to validate the research findings in this study. The results indicate that a proper system configuration can increase energy savings in spaces with active shade operation.
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Chapter 1 INTRODUCTION

1.1. Background

Integrating daylight with artificial lighting is a recognized good practice for sustainable building design (Yu and Su 2015). Lighting systems with the application of photocontrol can save up to 77% of the lighting energy consumption, depending on the space type and type of control (Li and Lam 2003, Tzempelikos and Athienitis 2007, Williams, Atkinson et al. 2012a, Soori and Vishwas 2013), but designs incorporating daylighting control schemes are not popular in the United States and worldwide (Li and Lam 2003, Krarti, Erickson et al. 2005, Li, Cheung et al. 2014, Yu and Su 2015). The study conducted by Krarti and his colleagues pointed out that the lack of tools to efficiently quantify system sustainability was a major reason for its low application rate (Krarti, Erickson et al. 2005). Later, in 2009, Mardaljevic and his research group argued that the most commonly used metric, daylight factor, is not considered effective in system performance evaluation since only the sky light contribution is included (Mardaljevic, Heschong et al. 2009). The partial understanding of the daylight availability in an interior space using daylight factor (Yu and Su 2015) causes difficulties for designers to generate standardized daylighting designs with high quality (Mardaljevic, Heschong et al. 2009). To resolve these issues, recent energy policies proposed the use of a few climate-based illuminance metrics and encouraged daylighting applications (CEC 2013, USGBC 2014). The calculation of these metrics, such as Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), etc., involves and relies on computer simulations (IESNA 2012). In the past two decades, the simulation tools have been improved in accuracy and validated to be reliable (Judkoff 1988, Grynberg 1989, Reinhart and Walkenhorst 2001, Reinhart and Andersen 2006, McNeil and Lee 2013, Yoon, Moon et al. 2016). Developments in the computer hardware and software systems also make an annual simulation more affordable in time and cost.

Increased reliability of the simulation results provides a solid base for system performance analysis. Research has gradually paid additional attention to daylight system performance such as maintaining desired illuminance, improving visual comfort and increasing energy savings (Li and Lam 2003, Mardaljevic, Heschong et al. 2009, Tzempelikos and Shen 2013, Caicedo, Pandharipande et al. 2014, Meugheuvel, Caicedo Fernández et al. 2014, Shen, Patel et al. 2014, Mistrick, Casey et al. 2015). The performance basis for a photocontrol system is the ability and
the precision of a photosensor to track daylight on the target plane. The responses of photosensors were found to be sensitive to multiple factors such as the sky conditions (Littlefair, Aizlewood et al. 1994, Choi and Mistrick 1998, Kim and Song 2007), the sensor position, and sensitivity distribution (Mistrick and Sarkar 2005, Yoon 2006), etc. Shading devices, typically applied in daylight delivery systems to improve the visual comfort by preventing direct sunlight penetration (Tzempelikos and Shen 2013), add additional complexities to the sensor response. Research conducted by Park and others with the focus on performance sensitivity to the roller shade height revealed that the impact of the shade height was not simply linear (Park, Choi et al. 2011). On the other side, research shows that estimation of a daylit building’s energy savings is dependent on the blind use pattern (Van Den Wymelenberg 2012, ul Haq, Hassan et al. 2014). Furthermore, the control strategies of automated shades vary with the energy or visual comfort concerns (Van Den Wymelenberg 2012) and are not expected to achieve a common solution for various daylight delivery system designs. Active or non-active use of different shading systems makes the prediction of photosensor response extremely difficult, and thus risks poor photocontrol system performance.

1.2. Research Overview

Motivated by the past studies, this research aims to investigate the performance of photocontrol systems across shade settings, and to provide common features or setups of a system that maintains the work plane illuminance close to target with reduced variance due to the climate conditions as well as the shade settings. A simulation-based statistical analysis procedure was applied to rank the significance of each factor and their interactions in parametric simulations of photocontrol system performance. Employment of this procedure is likely to result in smart device investment, proper layout, accurate response, and greater energy savings in photocontrol systems with active shade operation.
1.3. Dissertation Outline

Chapter 1 overviews the benefits of a photocontrol system, the importance of system performance and the incompleteness in system performance analysis across shade settings. General research objectives are introduced in this chapter.

Chapter 2 reviews relevant literature about the basics of daylighting, evolution of the simulation methodologies, and the performance of a photocontrol system. The advantages and shortcomings of the existing photocontrol system performance studies are summarized at the end of this chapter.

Chapter 3 states the research hypotheses and objectives.

Chapter 4 introduces the procedures applied to evaluate and compare photocontrol system daylight-tracking ability. These procedures include the simulation process for parametric modeling of photocontrol systems, the daylight-tracking ability comparison criteria, and the application of statistical models.

Chapter 5 and Chapter 6 investigate the photocontrol system performance at fixed shade settings and across different shade settings, respectively. The results were based on five-phase matrix-based Radiance daylight simulations. Klems BSDFs were used in seven general shade settings. An additional shade option with the daylight re-directing LightLouver™ system was simulated separately. LightLouver redirects daylight through strong specular reflections and works best in a south-facing space. Tensor-tree BSDFs provided by the manufacturer were used to generate the simulations with direct sunlight.

While the direction of the photosensor was found of great importance in Chapter 5 and Chapter 6, the abundance of the signal was also found to be crucial in preventing fluctuations of the total signal that may result from the human behavior involved environment changes in real practice. Chapter 7 was added to explore study cases with photosensor aiming at smaller angle steps towards the back wall. The results provide alternative system setups that receive higher daylight signal and provide acceptable performance.

Chapter 8 compares the energy consumption of photocontrol system setups in automated shade cases.
Chapter 9 concludes the research findings of the entire dissertation and provides the common features and setups of a photocontrol system integrated with multiple shade settings that deliver good system performance. At the end of this chapter, the limitations of this dissertation and future work in the field are addressed.
Chapter 2 LITERATURE REVIEW

2.1. Sky Models

Daylight calculations depend on the luminance distribution of the sky. At a particular geographic location, the daily and seasonal movements of the sun are predictable. In addition to the directional sunlight, the diffuse nature of the skylight varies with the insolation conditions. Actual sky luminance distribution data are large in size and less available. For the purpose of estimating the sky angular luminance, multiple sky luminance distribution models have been developed (DiLaura, Houser et al. 2010). CIE (Commission Internationale de l'Éclairage) proposed models of overcast, partly cloudy and clear sky with or without the sun (Darula and Kittler 2002). Perez and his colleagues presented a model with short (hourly) time step algorithms as a function of direct and global irradiance (Perez, Stewart et al. 1986, Perez, Seals et al. 1987, Perez, Ineichen et al. 1990, Perez, Seals et al. 1993). The Perez sky models (see Figure 2-1) have been applied to daylight simulation software and have been validated to be superior in accuracy over most other models in relation to the actual measurements (Littlefair 1994, Mardaljevic 1999, Igawa, Koga et al. 2004, Reinhart and Andersen 2006, Chamaidi 2009). Typical meteorological year (TMY) weather files are the major source of the hourly irradiance data applied for the annual daylight simulations. The TMY weather data sources are available for a wide variety of locations worldwide.
Figure 2-1. Perez sky models plotted for different turbidities $t$ (rows) and sun altitudes $\theta'$ (columns).
Each plot represents the entire hemisphere, centered at the zenith. (Lalonde, Narasimhan et al. 2010)

2.2. Daylight Simulation tools

Ray-tracing and radiosity are two major techniques for modeling light. Applications of radiosity are view-independent and address the interreflection of light from Lambertian surfaces.
Interreflections and subtle soft shadows can be captured and the calculation is fast, when the model is simple in geometry. The ray-tracing method, which is view-dependent, is more accurate when the model geometry is complex and the surfaces have specular components (Ashdown 1994). The transmission process in daylighting usually involves specular or partially specular reflections and refractions. Validation research indicates that radiosity methods provide less accurate daylighting calculation results as well (Gibson and Krarti 2015). The majority of design professionals conduct daylighting simulations using software that applies the ray-tracing method. Most of them are Radiance-based, a backward ray-tracing software package (Reinhart and Fitz 2006, Yu and Su 2015).


2.2.1. Daylight Coefficient Method

In 1983, Tregenza proposed the concept of daylight coefficients (Tregenza and Waters 1983). The amount of daylight on an interior point is contributed from two factors, the luminance of the sky and the interreflections from the surrounding surfaces. The contributions of the local changes to the sky luminance are not included in the computation, as Tregenza argued that those contributions were not significant. The concept then theoretically divides the celestial hemisphere into disjoint sky segments (See Figure 2-2(a)) and defines the contribution of each sky segment to the total illuminance on an interior sensor, based on the sensor position and orientation within the surrounding environment, as the daylight coefficient (Tregenza and Waters 1983, Mardaljevic 1999, Bourgeois, Reinhart et al. 2008). The equation can be expressed as:

$$DC_{\gamma\alpha} = \frac{E(x)_{\gamma\alpha}}{L_{\gamma\alpha} S_{\gamma\alpha}}.$$
where $L_{\gamma \alpha}$ is the luminance of the sky patch and $\Delta S_{\gamma \alpha}$ is the solid angle of the sky patch. The sky patch is identified by the solar altitude $\gamma$ and solar azimuth $\alpha$. $D_{\gamma \alpha}$ as a factor accounts for both the direct component from the sky dome and the inter-reflections between the surrounding surfaces. In daylight simulations, the geometry and material properties of the model are mostly assumed to remain unchanged during the space operation schedule. The luminance of each sky segment at each hour is simulated with the mathematical sky models using direct and diffuse irradiance values provided by the hourly information in the weather file. CIE skies and Perez skies are validated sky luminous distribution models that are commonly applied in the simulations (Perez, Seals et al. 1993, Littlefair 1994, Igawa, Koga et al. 2004). The illuminance from a particular sky patch onto the interior sensor point is the product of the daylight coefficient and the luminance of the sky segment (See Figure 2-3). At a particular hour, the illuminance on an interior sensor point is the sum of the product from each sky segment. Annual results can be achieved by multiplying the daylight coefficient matrix by the hourly sky segment luminous distribution matrix.

Figure 2-2. Sky Divisions
(Bourgeois, Reinhart et al. 2008)
Figure 2-3. Daylight coefficients
The contribution of each sky segment to the total illuminance on an interior sensor, based on the sensor position and orientation within the surrounding environment (Mardaljevic 1999)

The daylight coefficient method has been validated by a couple of comparative and empirical studies (Mardaljevic 1999, Reinhart and Walkenhorst 2001, Reinhart and Andersen 2006). Bourgeois, Reinhart and their research colleagues (Bourgeois, Reinhart et al. 2008, Laouadi, Reinhart et al. 2008) developed DAYSIM and improved the daylight-coefficient-based calculation using a more refined sky dome with continuous divisions (See Figure 2-2(b)). The sun’s positions are separately addressed to fit different levels of simulation accuracy (See the example in Figure 2-4). DAYSIM, DAYSIMps and DIVA are Radiance-based daylight calculation software with the application of the daylight coefficient method for annual simulations (Bourgeois, Reinhart et al. 2008, Reinhart and Wienold 2011, Mistrick, Casey et al. 2015). These software tools are also capable of electric lighting calculations with the input of the electric lighting information. DAYSIMps additionally addresses more details that assist photocontrol system design and performance analysis (Mistrick, Casey et al. 2015).
Figure 2-4. DAYSIM solar positions
Comparison of the distribution of the DAYSIM DDS solar positions versus the 65 DAYSIM altitude-dependent solar positions for Freiburg (47.988N) (Bourgeois, Reinhart et al. 2008)

2.2.2. Multi-phase Methods

Shortcomings of the daylight coefficient method that were discussed in recent publications (Konstantoglou 2011, Ward, Mistrick et al. 2011, McNeil 2013, McNeil and Lee 2013, Mistrick, Casey et al. 2015) can be summarized into two main aspects:

1. The daylight coefficient method does not provide efficient daylight and energy simulations for a complex fenestration system (CFS) that requires bidirectional optical measurements (Ward, Mistrick et al. 2011, McNeil and Lee 2013).

2. The direct contribution from the sun is integrated into sky patches with a solid angle much greater than the actual solar disk. Appropriately sized and positioned solar disks are required for more accurate modeling.
Multi-phase matrix-based methods were developed to address these challenges for efficient annual simulations. Matrix-based calculations rely on two basis, the bidirectional scattering distribution functions (BSDF) and the Klems hemispherical coordinate system (McNeil and Lee 2013).

2.2.2.1. Bidirectional Scattering Distribution Functions (BSDF)

The bidirectional scattering distribution functions generally characterize the directional distribution of light transmission and reflection from a surface or product (See Figure 2-5). The measurements of the BSDF data for a material can be obtained using an integrating sphere spectrophotometer or a goniophotometer (Konstantoglou 2011). Designers can access measured material properties through a database linked to Window6. Radiance also provides users a calculation module, genBSDF, to generate BSDF data for arbitrary CFS. The simulated BSDFs have been validated to be comparable to the goniophotometer measured results (McNeil, Jonsson et al. 2013). Radiance utilizes the BSDF data for daylight calculations with CFS (Ward, Mistrick et al. 2011). Two standard XML-based file formats have been defined in Radiance to store BSDF information. One applies a standard Klems resolution and the other applies a variable resolution in a tensor-tree representation (Rogers, Thanachareonkit et al. 2013).

Figure 2-5. Bidirectional Scattering Distribution
BSDF=BTDF+BRDF (Wikipedia)
2.2.2.1.1. Standard Klems Resolution BSDF

The Klems hemispherical coordinate system was developed in 1994 to provide solar heat gain estimations of a CFS using a matrix layer calculation (Klems 1994). The coordinate system divides the transmission and reflections into the incoming and the outgoing flows using the front and back-facing hemispheres (See Figure 2-6(a)). The two hemispheres applied in a Radiance BSDF calculation are divided into patches which have approximately the same size in solid angle (See Figure 2-6(b)). The 3D angular dimensions are converted to a 1-D cumulative table for stratified sampling (Ward 2014). The BSDF matrix maps the directional transmittance or reflectance for each ordered patch. Figure 2-7 shows an example of the BSDF data set with the incident direction within the range of patch No. 88 (McNeil 2014). Ward and his colleagues (Ward, Mistrick et al. 2011) argued that a higher resolution hemisphere, illustrated in Figure 2-8, may provide greater accuracy, particularly for highly directional reflection or transmission values (i.e. the light transmission of direct sun, the reflections from the mirror, or other scattering process caused by materials with a specular component). The size of the data set is huge in such cases, resulting in longer time to process inputs, outputs and calculations in simulations (Rogers, Thanachareonkit et al. 2013).

(a) Klems hemispherical coordinate system (Saxena, Ward et al. 2010)  (b) 3D view of the Klems hemisphere divisions used in Radiance with patches approximately the same size in solid angles

Figure 2-6. Klems hemispherical coordinate system concepts and applications
Figure 2-7. Typical example of standard Klems resolution BSDF (McNeil 2014)

(a) Treganza -145 divisions  (b) Reinhart MF:2 -580 divisions  (c) Reinhart MF:4 -2320 divisions

Figure 2-8. Orthographic projections of BSDF hemispherical division schemes (Ward, Mistrick et al. 2011)
Variable resolution BSDF’s in a binary tensor-tree representation (See Figure 2-9) adaptively subdivide the solid angle to a higher level of discretization for sharp and rapid directional value changes (Ward 2014). Radiance tensor-tree BSDF’s are based on two concepts: the tensor and the Shirley-Chiu low distortion map. Tensors are used to describe the general relativity between geometric objects. Tensors with rank-1 could be considered as a vector. Rank-2 tensors extend to a matrix. Higher rank tensors stack to higher dimension matrices (Lebedev and Cloud 2003). Figure 2-10 illustrates a typical structure of a rank-3 binary tensor. In Radiance simulations, a rank-3 tensor is used for isotropic BSDFs and a rank-4 tensor is used in anisotropic conditions. When the level of the tensor consists of a set of values that are not statistically different from each other, all sibling-leaf voxels can be folded over to an average value, but when every individual value is unique or change rapidly to the nearby ones, the structure of the branch is preserved. Recursion of the process to the entire tree results in efficient representations and small size file storage. Under similar accuracy power, the processing time for inputs and outputs is significantly reduced. Compared to the BSDF’s in same resolution Klems divisions, a rendering application of BSDF’s in a tensor-tree representation is faster and shows improvements in the accuracy (Ward 2014).

The domain of the tensor tree maps is square, but the sampling of BSDF requires hemispherical reallocation (Ward 2014). A mapping method (See Figure 2-11) developed by Shirley and Chiu (Shirley and Chiu 1997) was applied to resolve the transformation between a square and a disk, extending to a hemisphere. The mapped regions are less distorted in imaging and preserve sufficient accuracy for the stratified ray-trace sampling (Ward 2014). The tensor tree BSDF is not in exact matrix format and is only available for rendering or single time step simulations. Currently, annual simulations based on the multi-phase methods require customized matrix transformations for tensor tree representations and thus are not competitive in time savings. The general process is still under development.
Figure 2-9. Typical example of variable resolution BSDF in tensor-tree representations (McNeil 2014)

Figure 2-10. Example of rank-3 binary tensor tree for an isotropic BSDF (Ward 2014)
2.2.2.2. The Three-Phase Method

The three-phase method extends from the daylight coefficient method and breaks it down into three different phases of luminous flux transfer. The three phases are visually illustrated in Figure 2-12:

Phase 1, shown in Figure 2-13(b): Light transfer from the sky (patches) to the outside surface of the building fenestration (D, daylight matrix)

Phase 2, illustrated in Section 2.2.2.1.1: Light transfer through the fenestration system (T, transmission matrix: BSDF in standard Klems resolution representation)

Phase 3, shown in Figure 2-13(c): Light transfer from the fenestration’s inside surface onto the interior directional viewpoints (V, view matrix)

Each phase of light transfers is represented by a matrix. The illuminance on an interior measurement point is then expressed as:

\[ i = VTDs \]

where the input sky matrix \( s \) (e.g. Figure 2-15(b)) is a set of sky patch luminance values for a particular time or in an annual sequence. An array of measurement points can be applied in the V matrix to provide a desired set of simulation values for numerical results as well as pixel values for a rendering (Ward 2014). A rendering example is shown in Figure 2-13(d). The three-phase method is also known as the Dynamic Radiance Approach. The speed of the calculation and the
incorporation with arbitrary BSDFs for CFS are the principal advantages of this method over the standard daylight-coefficient method. The division of the phases into exterior, fenestration and interior grants researchers and designers the reuse of the partial results, which saves a significant amount of time for parametric designs and offers a better chance to optimize the system (Saxena, Ward et al. 2010). The validation case study conducted by McNeil and Lee in 2013 indicates the calculation results of the three-phase method are generally reliable (McNeil and Lee 2013). In spite of these benefits in annual simulations, the three-phase method with standard Klems resolution yields some limitations in direct light transmission and shadowing. Figure 2-14(b), generated by the three-phase method, shows blurred edges and less detail for the shadowing from the venetian blinds compared to a full simulation shown in Figure 2-14(a), although the time consumed was significantly less (Saxena, Ward et al. 2010).

**Figure 2-12.** General process of the three-phase method
(McNeil 2013a)
Figure 2-13. Steps of three phase calculation.
The images represent 3pm on a clear solar equinox with venetian blinds having curved, half-specular louvers set to horizontal (Saxena, Ward et al. 2010).
2.2.2.3. The Five-Phase Method

The five-phase method is an extension of the three-phase method and designed to improve the performance of a three-phase calculation by addressing the direct component of the transmission. In the five-phase method, the contribution from the direct solar component into a room is separately computed to achieve better accuracy. The equation adapts the three-phase method:

\[ i_{5ph} = VTD \quad dTDs + C_{dssun} = i_{3ph} - Vds + C_{dssun} \]

Where:

- \( V, T, D \) and \( s \) stand for the view matrix, transmission matrix, daylight matrix, and sky matrix respectively, the same as the definition in the three-phase method.
- \( V_d \) and \( D_d \) stand for the daylight matrix and view matrix from the direct solar radiation.
- \( C_{ds} \) stands for the daylight coefficient matrix for the direct sun.
- \( s_{sun} \) is the direct sun matrix. (McNeil 2013)

The Tregenza sky model with 145 patches at about 10.15° cone opening angle for each, or similarly the Reinhart continuous sky at approximately the same resolution, was the standard application for standard sky matrix calculations. Three nearby patches of the sun’s absolute location were selected for luminance interpolation, resulting in a resolution closer to 24° (illustrated as the yellow colored patches in Figure 2-15(b)). The contribution from the sun is averaged into three patches and causes a wide margin of error to the sky luminance gradient illustrated in Figure 2-15(a) (Saxena, Ward et al. 2010). To improve the computational accuracy
of the sun in the five-phase method, the radiation of a single sky patch adjusted to the solid angle of the sun is used to generate the $C_{ds}$ and $s_{sun}$.

![Sky luminance gradient](image1)

(a) Sky luminance gradient

![Discretized sky luminance](image2)

(b) Discretized sky luminance (Tregenza or Reinhart MF:1)

**Figure 2-15.** Sky luminance gradient distribution and discretized models (McNeil 2013)

Two solutions are proposed for the sun’s position. One refers to the higher-level resolution of the existing Reinhart sky model for the sun’s positions (e.g. Figure 2-16(a)). The finest resolution sky model contains as many as 5185 sun positions (McNeil 2013a). The other (shown in Figure 2-16(b)), as proposed by Casey and Mistrick, uses the positions of the sun based on the solar analemma pattern (Casey and Mistrick 2015).

The basic procedure of conducting a five-phase method annual calculation is:

- **Phase 1 to 3**: Perform a three-phase simulation (Shown in Figure 2-17(a))

- **Phase 4**: Subtract the direct solar contribution calculated by the three-phase simulation (Shown in Figure 2-17(b))

- **Phase 5**: Add a direct solar contribution that is more accurately simulated (Shown in Figure 2-17(c)).
A five-phase method calculation example is rendered in Figure 2-17(d), in which the shadowing of the venetian blinds is clearly observed. The five-phase method has not yet been validated, but as an extension of the validated three-phase method with better direct component calculation accuracy, the five-phase method is reliable for full annual advantageous daylighting simulations.

Figure 2-16. Two solutions proposed for the sun’s positions (McNeil 2013a, Casey and Mistrick 2015)
2.3. Photocontrol Systems

Daylight integrated photocontrol systems dim down or switch off the electric lighting according to a photosensor signal. Systems with good performance are capable of maintaining the work plane illuminance and saving a reasonable amount of energy at the same time.
2.3.1. Energy Performance

In 2012, Williams and his colleagues summarized the energy performance of lighting control systems in their meta-analysis (Williams, Atkinson et al. 2012a, Williams, Barbara Atkinson et al. 2012b). In the 73 daylighting integrated photocontrol cases they reviewed, the average energy savings were about 39% of the system total. The savings of actual measurements were 28% on average, whereas the simulated case yielded a higher estimation at 48%. Thirty percent of the photocontrol study cases were carried out in educational buildings and the savings were the highest on average at 49% among all building types. They concluded that the photocontrol systems demonstrated high energy saving potential but the savings were overestimated in the simulation cases. The research by Ramos and Ghisi (Ramos and Ghisi 2010) focusing on EnergyPlus indoor illuminance estimation drew similar conclusions. The simplified models were considered the primary reason for overestimation, particularly in the energy modeling software built for thermal performance. Radiance, specializing in lighting and daylighting calculations, allows sophisticated modeling details for geometry and material properties and is validated to provide reliable and close-to-actual results. Recent developments of Radiance in simulating daylighting systems with complex fenestration further improve the modeling accuracy (McNeil and Lee 2013). Challenges, such as the operation of shading devices, proper system installation, and calibration, still remain open for discussion to provide system with energy savings that are closer to the simulations (Heschong, Howlett et al. 2005, Van Den Wymelenberg 2012).

2.3.2. Photosensor Performance Analysis

The response of the photosensor was one of the primary concerns in daylighting research. Studies have been carried out in field measurements and computer simulations (Littlefair, Aizlewood et al. 1994, Mistrick and Thongtipaya 1997, Choi and Mistrick 1998, Littlefair and Motin 2001, Mistrick and Sarkar 2005, Kim and Song 2007, Chen and Mistrick 2013, Mistrick, Casey et al. 2015). Before the standard daylight coefficient method was introduced into Radiance and dominated applications for daylighting calculations, annual simulations were time consuming. Dates with representative solar positions such as solstice and equinox were the commonly selected dates (Mistrick and Thongtipaya 1997, Kim and Song 2007). Sky conditions were separately modeled using CIE or IESNA skies in these two studies. The results indicated that a
partially-shielded photosensor provides a good response (Mistrick and Thongtipaya 1997, Kim and Song 2007). The field study of photocontrol system in a space with innovative fenestration conducted by Littlefair and Motin observed similar performance patterns (see Figure 2-18). The variation in the signal versus work plane illuminance ratios were greater in clear sky conditions (Littlefair and Motin 2001). The control algorithm and the depth of the photosensor have been found critical to photosensor performance as well (Mistrick and Sarkar 2005).

![Figure 2-18. The photosensor signal plotted against work plane illuminance with clear glazing in clear sky and overcast sky conditions (Littlefair and Motin 2001)](image)
2.3.2.1. Impact of the Shadings

Most research has been conducted with fixed shade position (Littlefair, Aizlewood et al. 1994, Mistrick and Thongtipaya 1997) or assumptions of shade schedule based on the solar positions (Mistrick and Sarkar 2005, Kim and Song 2007). Wankanapon, Tzempelikos and Shen developed their control strategies for shade operation with comprehensive daylighting and system energy concerns (Wankanapon 2009, Tzempelikos and Shen 2013). Lee and Selkowitz conducted their monitored field study of photocontrol systems with the automated interior shade using a commercially available control strategy. The results demonstrated that properly commissioned systems delivered reliable performance with high energy savings (Lee and Selkowitz 2006). DAYSIM (LBNL 2016) and DAYSIMps with built in functions of solar profile angle and shade sensor signal provide daylight-coefficient-based simulation calculations with automated shade operation. Mistrick and others addressed the simulation-based photocontrol system design and analysis with automated shades to improve the interior daylighting quality and photosensor response reliability (Casey and Mistrick 2015). But, it is noticeable that the application of automated shadings was only 1-2% in building industry upon the time of 2006 (Lee and Selkowitz 2006). Additionally, Van Den Wymelenberg concluded in a review on shade operation that manual operation of shades was still the majority of all applications. Van Den Wymelenberg also concluded that manual operation frequency is considerably low. The primary reason for manual shade adjustments was found relating to glare. Automated shading operation showed inconsistent adjustment patterns (Van Den Wymelenberg 2012). Commercially available automated shade controls vary with different aspects of concerns additional to lighting such as energy consumed by the heat transfer (mainly cooling load) (Tzempelikos and Shen 2013). While agreement in shade control strategies may not be achieved across the various daylight delivery systems, a study by Park and his colleagues indicated that operation of a shading device affects system performance and the relationship between the signal response and roller shade heights is not simply linear. The sky conditions also showed inconsistent influence on the sensor response when interacting with different roller shade heights (Park, Choi et al. 2011). Other than Park’s study, few publications addressed the impact of shading settings on system performance.
2.3.2.2. Photosensor Modeling

Photosensors can be modelled physically or using functions for material properties. Physically modelled photosensors were commonly used to simplify the simulation process before the computer simulation becomes time affordable to address small details (Mistrick and Thongtipaya 1997, Kim and Song 2007).

Modeling the continuous spatial sensitivity of a commercial photosensor usually requires the use of a material property function. In 2002, Ehrlich proposed a method with a built-in module in Radiance for photosensor sensitivity modeling (Ehrlich, Papamichael et al. 2002). Mistrick and Sarkar conducted their simulations using the module “PSENS” developed by Ehrlich (Mistrick and Sarkar 2005). Reinhart and Anderson offered an alternative to modeling a photosensor spatial sensitivity distribution when they developed the Radiance material type “transdata” to adjust the angular transmittance properties of a material (Reinhart and Andersen 2006). Yoon tested another material type “brightdata” (See Figure 2-19) using the Radiance daylight coefficient method and achieved reliable photosensor signal results for an annual simulation. A “*.dat” file used in the material definition provides the information on the photosensor sensitivity. The format of the file is similar to a luminaire photometry file. As an example, the “45cosine.dat” used in the photosensor modeling (See Figure 2-19) corresponds to the photosensor sensitivity illustrated in Figure 2-20 (Yoon 2006). With Radiance’s built-in modules, arraying or re-aiming the photosensor is simple in process. This photosensor modeling method is plugged into DAYSIM to provide signal controls for shades and electric lighting systems (LBNL 2016).
void brightdata cos45finc
5 noop 45cosine.dat acos(-Dz)/DEGREE atan2(-Dy,-Dx)/DEGREE+180
0
0

cos45finc trans cos45trans
0
0
71110011

cos45trans sphere cos45sph
0
0
40-441431

- noop = return no value (i.e. noop(v) = v)
- 45cosine.dat = the file name for the directional sensitivity distributions;
- . = dot character means that no additional function file is needed;
- acos(-Dz)/DEGREE = transformation between z-direction vector and altitude angle; and
- atan2(-Dy,-Dx)/DEGREE+180 = transformation between x and y direction vectors and azimuth angle

**Figure 2-19.** Example "*.rad" file modeling photosensor spatial sensitivity using material type “brightdata”
(Yoon 2006)

![45° cosine](image)

**Figure 2-20.** Modeled photosensor spatial sensitivity of Figure 2-19
(Yoon 2006)
2.4. Summary and Research Gaps

Field measurements and simulations demonstrate that properly commissioned daylight integrated photocontrol systems are good practice of sustainable design with great energy savings potential (Lee and Selkowitz 2006, Williams, Atkinson et al. 2012a, Shen, Patel et al. 2014, Yu and Su 2015). The energy savings predicted by simulations were mostly overestimated. The primary reason is considered to be the simplified simulation models. After the introduction of the standard daylight coefficient method into Radiance, annual simulations became less time consuming (Mardaljevic 1999, Reinhart and Andersen 2006, Bourgeois, Reinhart et al. 2008). The use of Perez skies along with the input of typical meteorology year weather data increases the prediction accuracy and makes the simulation results statistically reliable and inferable to the real space (Perez, Seals et al. 1993, Littlefair 1994, Reinhart and Andersen 2006). Recent Radiance developments on the matrix-based multi-phase method calculations provide efficient and accurate simulations of a CFS and allow for the reuse of the matrices for parametric designs (Ward 2014).

Past research addressed multiple factors that may affect photocontrol system performance. The photosensor directional sensitivity distribution, its location and direction were found to be key determinants of photosensor performance (Mistrick and Thongtipaya 1997, Littlefair and Motin 2001, Mistrick and Sarkar 2005, Kim and Song 2007). The photosensor response also varies with sky conditions (Littlefair and Motin 2001, Park, Choi et al. 2011). The prediction of the sensor response with the application of a shading system was shown to be more complicated (Park, Choi et al. 2011). Some of the research in the past used customized strategies of automated shading to address the operation patterns, but field studies show few application cases with automated shading, and control strategies often apply visual or energy concerns. The adjustments of manual shades are less frequent, but relate to seasonal or daily sun profile. Few photocontrol system performance analysis studies were found with special focus on the impact of shade settings. Taking advantage of the efficient multi-phase simulation method, this study is intended to fill a research gap in investigating the impact of shade settings on photocontrol system performance.
Chapter 3 HYPOTHESES AND OBJECTIVES

The response of a photocontrol system is sensitive to the characteristics of photosensor as discussed in the literature review. The photosensor signal versus illuminance ratios (S/E) are critical and can be used to characterize the response accuracy of a photocontrol system (Park, Choi et al. 2011). In the widely applied linear control systems, the S/E ratios are assumed constant, but while the actual ratios from the electric lighting are constant, the ratios from daylight vary with climate conditions. Commercially available sensors installed close to the window, receiving signals from sunlight patches, may result in very high ratios. Calibration conducted under these high ratio conditions may cause the system to overshoot the illuminance target and result in lower energy savings, whereas calibrations on overcast days with a low S/E ratio will not provide sufficient light levels for most sunny hours within the dimming range. A photocontrol system configuration that results in closer ratios across different sky conditions is generally preferred to maintain sufficient light levels and good energy savings at the same time. Research indicates that the impact of shade settings on the S/E ratios is not simply linear (Park, Choi et al. 2011). When shades are partially lowered, signal drop was found to be less, proportionally, than the decrease in illuminance on the work plane. This occurs because the photosensor usually receives more light contribution from the exterior ground reflections than the work plane receives from the sky. Variations in S/E ratios may cause large fluctuations in the electric light output with poorly maintained work plane levels and thus be less effective in providing satisfactory performance. A linear photocontrol system algorithm provides better performance when the variance in S/E ratios during the operation schedule is low, which should be the focus of a good design/layout.

Recent developments in software have addressed efficient daylight simulations with CFS. The application of statistically valid weather data makes the simulations inferable. The reuse of matrices fit the purpose of efficient parametric performance analysis. To date, few studies have used a matrix-based method to conduct photocontrol system performance analysis.

This research aims to investigate the response of photocontrol systems across shade settings, and to analyze the relationships between the characteristics of the photosensor and system performance.
The hypotheses for this study are:

1. Different shade settings cause significant fluctuations in photocontrol system response (significant fluctuations in S/E ratios)
2. Characteristics of a photocontrol system (the location of the photosensor, the spatial sensitivity of the photosensor, the aiming angle/direction of the photosensor) and some of their interactions are statistical significant factors that contribute to system performance across shade settings.
3. The interactions between the characteristics of a photocontrol system and some properties of the daylight environment (such as the sky conditions, the orientation of the space, the geographical information of a site, and the obstruction of the view in front of the CFS) are statistically significant factors that contribute to system performance.
4. Analysis can be used to rank these factors in terms of level of importance.
5. The variance in S/E ratios that results from the changes in exterior daylight conditions and across shade settings can be reduced by setting up a system based on the statistical analysis results (the significant contributors) provided through simulations.

The objectives of this study include:

1. To provide valuable information how each characteristic of a photocontrol system impacts the system performance in different environments and under different system setup conditions (across shade settings)
2. To provide valuable information on how the characteristics of a photocontrol system interact with different environment conditions or system setup conditions, across shade settings.
3. To identify common features of system configuration that properly maintain the work plane illuminance and save reasonable amount of energy.
4. To propose statistical methods and analysis procedures that designers or manufacturers may follow and customize, in order to optimize the configuration of their photocontrol systems.
4.1. Modeling Details

Sidelighting is the most common daylight approach and remains the most common daylighting strategy in building applications (McNeil and Lee 2013). A review by Williams and his colleagues (Williams, Atkinson et al. 2012a, Williams, Barbara Atkinson et al. 2012b) concluded that the educational building type provided the greatest energy saving potential for daylighting integrated photocontrol among all studied building sectors. A classroom has therefore been selected for this study. The selected space for this study is based on a real space, EEE 123 located at Penn State University. The complete real model is non-symmetric in geometry and material, which may introduce unnecessary biases and mask the significance of factors (independent variables) in the scientific experiments. A symmetric model 35 ft W / 25 ft D / 9.7 ft H (10.7 m W / 7.6 m D / 2.9 m H), shown in Figure 4-1, will be used for a parametric performance analysis case study. Material properties for the space are mainly based upon measurements and are summarized in Table 4-1.

Figure 4-1. Classroom model used for parametric performance analyses
<table>
<thead>
<tr>
<th>Material properties of the study space</th>
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</thead>
<tbody>
<tr>
<td>Reflectance</td>
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<tr>
<td>Floor</td>
</tr>
<tr>
<td>Wall</td>
</tr>
<tr>
<td>Ceiling</td>
</tr>
<tr>
<td>Window Frame</td>
</tr>
<tr>
<td>Ground</td>
</tr>
<tr>
<td>Transmittance</td>
</tr>
<tr>
<td>Glazing</td>
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</table>

4.2. Simulation Cases
4.2.1. Parametric Models with Shade Settings

The general purpose of this study is to identify photocontrol system configurations that minimize the impacts resulting from different site conditions and shade settings. The typical application in the industry, a ceiling mounted photosensor, is applied in this study. As discussed in Chapter 3, the key is to produce a photocontrol system layout where the photosensor signal versus work plane illuminance ratio (S/E) should have minimum variance. S/E is therefore the primary dependent variable considered in this study.

The following situations were found that may affect the S/E ratio (not limited to the listed cases):

- First, the climate conditions of different sites naturally create a difference in daylight availability. The exterior environment, façade orientation, and properties of the fenestration (e.g. window to wall ratio, transmittance of the window, exterior shading devices, etc.) generate variations in the interior daylight distribution and determine the hours when sunlight penetrates into the room and when shades may need to be applied. Mistrick and Sarkar (Mistrick and Sarkar 2005) studied the photosensor performance in five classrooms with different daylight delivery systems. Both climate conditions and daylight delivery systems introduced significant variations in S/E ratios. The field study by Littlefair and Motin observed that S/E ratios were higher during sunny hours than those obtained during overcast hours. (Littlefair and Motin 2001)
- The work plane reference point used for calibration purposes (i.e. the critical point) is usually located deeper into the room and provides a more consistent response with
changing sky conditions compared to a photosensor located closer to the window which sees a larger portion of the exterior (See Figure 4-2). (Mistrick and Sarkar 2005)

- When sunlight penetrates onto the floor, a photosensor may pick up a high signal, causing S/E to increase. Sensors with a limited view field may see a significant signal increase when sunlight patches are within their field of view, which results in significant over-dimming of the system for these conditions (Mistrick and Sarkar 2005).

- The operation of a shading device may introduce additional variations (Park, Choi et al. 2011). When the shades partially cover window apertures, the view of the exterior may be blocked by the shade and cause significant changes in signal compared to work plane illuminance. When the photosensor sees sunlight patches transmitted through holes or openings in the shade, or can view sunlight reflections from the exterior, the S/E ratio is usually higher than a condition where the entire signal comes purely from reflected skylight (Mistrick and Sarkar 2005).

- On sunny days, when the daylight is redirected by shading devices onto a ceiling mounted photosensor, such as from blinds or specular louvers, the ceiling is much brighter than during the overcast hours, causing a significant increase in S/E (Littlefair and Motin 2001).

(a) Clear Sky Condition Work Plane Illuminance Contour 03/19 08:00 AM
Partly Cloudy Sky Condition Work Plane Illuminance Contour 03/06 08:00 AM

Overcast Sky Condition Work Plane Illuminance Contour 06/11 17:00 PM

Figure 4-2. Work plane illuminance contours under different sky conditions with similar critical point illuminance.

The space is facing South with no exterior obstructions and is located in State College, PA.

Although the impacts of climate conditions and photocontrol system configurations on the S/E ratios have been widely discussed, as stated above, variations in S/E ratios caused by combinations of these features and shade settings remains unclear. To explore the response (S/E) in a comprehensive daylight integrated photocontrol system integrated with multiple shade settings, four categories of variables were selected as the independent variables for this study: environmental variables, sky conditions, photocontrol system configurations, and shading applications. Five-phase matrix-based Radiance calculation modules (McNeil 2013) were applied to simulate work plane illuminance and photosensor signal. The settings for each independent
variable and the corresponding five-phase simulation matrices affected are listed and summarized in Table 4-2. The case studies were designed to avoid bias from systematic errors, to provide some variability in the photocontrol system design, and to deliver valuable information for control system product selection and layout.

<table>
<thead>
<tr>
<th>Table 4-2. Summary of independent variables and corresponding matrices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category</strong></td>
</tr>
</tbody>
</table>
| Environmental | Site | • Houston, TX  
• Phoenix, AZ  
• Seattle, WA  
• State College, PA | S | 4 |
| Orientation | | • South  
• East  
• North | D | 3×2=6 |
| Exterior obstructions | | • No obstructions  
• View of the sky blocked at 23 degree profile angle | -- | -- |
| Sky Conditions | | • Overcast  
• Partly Cloudy  
• Clear | -- | -- |
| Photocontrol System Configurations | Field of View (Illustrated in Figure 4-3) | • Narrow (Biquadratic-Cosine correction)  
• Wide (Cosine correction)  
• Cut-off at 60 Degrees (Cosine correction) | V | 3×3=9 |
| Aiming Direction | | • 45° towards window (F45)  
• Straight Down (D)  
• 45° towards back of the room (B45) | -- | -- |
| Position Depth | | • 3 ft / 7 ft / 11 ft | -- | -- |
Shading Applications Settings (See Table 4-4 and Table 4-5) 6 Shade settings + 1 Unshaded window = 7 General Combination Subtotal 7×4×3×2×3×3×(3)×(3) (General) = 1512 cases (13608) Comparisons Total 9×3(V) + 9×3(V_d) + 8 (T) + 6×3(D) + 6×3(D_d) + 4(S) + 4(S_d) + 7×6×9(C_d) + 4(S_{sun}) = 488 matrices

*Shading settings and matrix calculations are summarized in Table 4-4 and Table 4-5.

(a) Narrow Biquadratic-Cosine (cos^4\phi) correction  (b) Wide Cosine correction (Lambertian)  (c) Cut-off at 60 degrees Cosine correction

**Figure 4-3.** Photosensor spatial sensitivity distributions

The selections of the independent variables in the first category (Environmental Variables) are based on the study of Reinhart and his colleagues (Reinhart, Mardaljevic et al. 2006), which
indicated that these variables may affect the daylight distribution within interior spaces. The second category, the Sky Conditions, are considered critical to system performance in multiple published studies (Littlefair and Motin 2001, Kim and Song 2007, Park, Choi et al. 2011). The annual simulations were conducted with TMY weather files. Sky conditions were then categorized into three main groups based on irradiance values and solar position (Littlefair 1994, Umemiya and Kanou 2008). The selection basis for the third category (Photocontrol System Configurations) comes from the earlier photosensor performance research covering the impacts of photosensor sensitivity distributions, aiming direction, and location (Choi and Mistrick 1998, Littlefair and Motin 2001, Mistrick and Sarkar 2005, Kim and Song 2007, Chen and Mistrick 2013, Mistrick, Casey et al. 2015). Shading operation was discussed less in previous photocontrol performance studies. The selections in the fourth category are the focus of this study, designed to fill in this research gap. The selection of the shading settings accounts for variability in transmission and reflection processes. Shading systems with specular and diffuse transmittance, and different reflectance characteristics, are included. Fabric shades and horizontal blinds are widely used in the industry and applied in this study. The properties of the selected shading materials are summarized in Table 4-3. The transmission matrices (Klems BSDF’s) of shading systems were generated by the Radiance “genBSDF” module for the configurations listed in Table 4-4. The settings of the shading devices and the matrices used in each study case are summarized in Table 4-5.

<table>
<thead>
<tr>
<th>Table 4-3. Material properties of the shading systems</th>
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<tbody>
<tr>
<td><strong>Product</strong></td>
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<tr>
<td><strong>Product</strong></td>
</tr>
<tr>
<td>T&lt;sub&gt;v&lt;/sub&gt;</td>
</tr>
<tr>
<td>R&lt;sub&gt;s&lt;/sub&gt;</td>
</tr>
<tr>
<td>R&lt;sub&gt;d&lt;/sub&gt;</td>
</tr>
<tr>
<td>Of</td>
</tr>
</tbody>
</table>

* T<sub>v</sub>: visual transmittance; R<sub>s</sub>: specular reflectance; R<sub>d</sub> diffuse reflectance; Of: openness factor
* The fabric shades were modelled with the Radiance “trans” material type
### Table 4-4. Shading device types and applications

<table>
<thead>
<tr>
<th>Shading Device Type</th>
<th>Covering Window Pane</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse Fabric Shades</td>
<td>Upper window pane</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>Lower window pane</td>
<td>(2)</td>
</tr>
<tr>
<td>Fabric Shades with 3% openness factor</td>
<td>Upper window pane</td>
<td>(3)</td>
</tr>
<tr>
<td></td>
<td>Lower window pane</td>
<td>(4)</td>
</tr>
<tr>
<td>Horizontal Blinds</td>
<td>0° covering entire window pane</td>
<td>(5)</td>
</tr>
<tr>
<td></td>
<td>45° covering entire window pane</td>
<td>(6)</td>
</tr>
<tr>
<td>None</td>
<td>Upper window pane</td>
<td>(7)</td>
</tr>
<tr>
<td></td>
<td>Lower window pane</td>
<td>(8)</td>
</tr>
</tbody>
</table>

### Table 4-5. List of shading device settings with a count of the required matrices

<table>
<thead>
<tr>
<th>Shade Settings</th>
<th>Shading Applications by Device Types</th>
<th>Required number of matrices $V_{TDS} - V_dT_dS + C_{dsS_{sun}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case with no shading (FWIN)</td>
<td>(7) + (8)</td>
<td>$(9 \times 2 + 2 + 6 \times 2 + 4) + (9 \times 2 + 6 \times 2 + 4) + (9 \times 6 + 4) = 128$</td>
</tr>
<tr>
<td>Diffuse Fabric Shades on upper window pane (US_NO)</td>
<td>(1) + (8)</td>
<td>$(9 \times 2 + 2 + 6 \times 2 + 4) + (9 \times 2 + 6 \times 2 + 4) + (9 \times 6 + 4) = 128$</td>
</tr>
<tr>
<td>Diffuse Fabric Shades fully closed (FS_NO)</td>
<td>(1) + (2)</td>
<td>$(9 \times 2 + 2 + 6 \times 2 + 4) + (9 \times 2 + 6 \times 2 + 4) + (9 \times 6 + 4) = 128$</td>
</tr>
<tr>
<td>Fabric Shades with openness on upper window pane (US_O)</td>
<td>(3) + (8)</td>
<td>$(9 \times 2 + 2 + 6 \times 2 + 4) + (9 \times 2 + 6 \times 2 + 4) + (9 \times 6 + 4) = 128$</td>
</tr>
<tr>
<td>Fabric Shades with openness fully closed (FS_O)</td>
<td>(3) + (4)</td>
<td>$(9 \times 2 + 2 + 6 \times 2 + 4) + (9 \times 2 + 6 \times 2 + 4) + (9 \times 6 + 4) = 128$</td>
</tr>
<tr>
<td>Horizontal Blinds 0° full coverage (HBLINDS)</td>
<td>(5)</td>
<td>$(9 \times 1 + 1 + 6 \times 1 + 4) + (9 \times 1 + 6 \times 1 + 4) + (9 \times 6 + 4) = 97$</td>
</tr>
<tr>
<td>Horizontal Blinds 45° full coverage (45BLINDS)</td>
<td>(6)</td>
<td>$(9 \times 1 + 1 + 6 \times 1 + 4) + (9 \times 1 + 6 \times 1 + 4) + (9 \times 6 + 4) = 97$</td>
</tr>
</tbody>
</table>
Taking advantage of the Radiance five-phase method (McNeil 2013), the matrices required by the independent variables are reusable. 488 matrices in total are required to conduct the 1512 combinations (See Table 4-2) of case studies. Radiance inputs allow the hourly signal and work plane illuminance to be calculated with grid point files (i.e. critical points). To compare the results of S/E ratios between shade settings, two work plane reference points on either side of the room at a 15’ depth (approximately 1.5×window head height) were used for the illuminance measurements (Reinhart 2005). The lower daylight illuminance from these two work plane sensors was employed in the S/E ratio calculations to account for interior non-uniform daylight distributions due to the sun’s position. A threshold for the reference point daylight illuminance of 200 lux was applied. The 200 lux refers to the typical range of light required from the dimmed zone in a photocontrol system when the target is 300 to 400 lux. When the daylight illuminance is greater than the threshold, the electric lighting zone adjacent to the windows can be operated at minimum dimming level and higher daylight conditions may not contribute to photocontrol system performance. Hence, these data were removed to prevent any skew in the S/E ratio findings.

4.2.2. Case Studies with Different Photosensor Aiming Directions

The outcome of the study described in the previous section and reported in Chapter 5 and Chapter 6 indicate that the aiming direction of the photosensor is the most important among the analyzed photocontrol configurations. A photosensor directed towards the interior was found to produce a significantly lower signal from daylight and may result in a narrower dimming signal range in a closed loop system. This may cause extra sensitivity to reflections from interior surfaces and may reduce the accuracy of the system response under real conditions. To analyze the magnitude of the signal and provide additional options for photosensor directions, additional studies (3024 comparisons) were conducted with a cosine-corrected photosensor directed 15° and 30° away from the window. These photosensors receive a larger portion of the daylight than the photosensor directed at a 45° angle.
4.2.3. Parametric Models with LightLouver Applications

To explore the impacts of shade settings with specular reflections, a specular light redirection system, LightLouver™ (shown in Figure 4-4), was considered. LightLouver redirects the daylight deeper onto the ceiling with curved specular louvers and is generally effective in south-facing conditions. Due to the limitations of current software, the five-phase matrix-based annual simulations cannot be fully processed by tensor-tree BSDF’s, which model specular reflections more accurately and efficiently. The highly directional sunlight reflection was therefore separated from the more diffuse sky and ground contributions. The sky and ground contributions in an annual system performance simulation was conducted using a three-phase method with standard Klems BSDFs, while the contribution from the direct sun was separately simulated applying the tensor-tree BSDFs in a daylight coefficient approach (the fifth phase). The model settings used for the LightLouver study are:

- State College, PA / Houston, TX / Phoenix, AZ / Seattle, WA
- South-facing
- No exterior obstructions
- Annual sky conditions: Overcast / Partly Cloudy / Clear
- Shade Settings: With / Without fabric shades (no openness) covering the rest of the window, and simulated by the matrix-based method
- Photosensor Field of View: Narrow / Wide / Cut-off
- Photosensor distances from window: 3 ft (0.9 m) / 7 ft (2.1 m) / 11 ft (3.4 m)
- Orientations of the photosensor: Down / Back 45°

Specular louvers redirect daylight onto the ceiling, which provide strong directional signals and are less likely to provide good photocontrol system performance with a photosensor that is tilted 45 degrees towards the window aperture.
4.3. Statistical Analysis

The dimming operation of a commercially available photosensor usually assumes a linear relationship between the photosensor signal and the work plane illuminance, and then applies this signal to electric light output. The purpose of the statistical analysis in this study is to investigate the photocontrol system configurations (system properties and layouts) that are least impacted by shade settings in combination with other site variables. The focus is the photosensor signal to the work plane illuminance ratio (S/E) over the range of conditions that may be present. More specifically, the purpose is to reduce the variance in S/E due to the shade settings and sky conditions. The response is a continuous variable, whereas the independent variables are categorical. The design of theoretical study cases is mostly balanced. ANOVA models are good fits to provide efficient and accurate statistical analyses for this type of experimental design.
4.3.1. The distributions of S/E ratios

When the photocontrol system configuration is fixed, the shapes of the S/E ratio distribution for each shade setting may be similar. Figure 4-5 shows an example of the S/E ratio distributions when the horizontal blinds are lowered compared to the condition when no shade is applied (clear glazing). The shapes of both distributions are similar, but the center of the two distributions are different. A system that applies a linear control algorithm, configured with the settings in Figure 4-5 and calibrated at a fixed slope (S/E ratio), may experience fluctuations across shade settings. When two configurations of photocontrol system are compared, both the shapes and the centers of the distributions may be different (See example in Figure 4-6). Thus, the features of the S/E ratio distribution are the basis of photocontrol system performance evaluation. However, due to the nature of daylight, as well as different photocontrol system configurations and environment variables, the distributions of the S/E ratios are not normal (See example in Figure 4-5 and Figure 4-6). The descriptive statistics that are best applied to normal distributions are not proper for analysis of skewed distributions. A normalization transformation process was initially considered (See Figure 4-7), but results indicated that a transformation process may cause a loss of the center and shape information that is valuable in explaining the system’s performance. To accurately quantify the shape and center of the S/E ratio distribution across the independent variables, the median and the normalized distribution width (NDW) were used. The NDW is derived from two steps. Firstly, calculate the width between the 75th percentile and the 25th percentile (Distribution Width: DW). Secondly, normalize the DW by dividing it by the median. The normalization process is required since the photosensor receiving a higher signal usually results in higher DW and vice versa. Direct comparisons of DWs do not provide complete information on the shape of the distribution. These two parameters, median and NDW, are the response (dependent variables) in the statistical analysis model.
**Figure 4-5.** S/E ratios when horizontal blinds are lowered vs. S/E ratios when no shade is applied.

The space is facing south with no exterior obstructions, located in State College, PA. The cosine-corrected photosensor is located 3 ft (0.9 m) deep into the room and directed 45° towards the window.

**Figure 4-6.** S/E ratios in the photocontrol system with a photosensor directed 45° towards the back wall vs. 45° towards the window.

The cosine-corrected photosensor is located 3 ft (0.9 m) deep into the room. The space is facing south with no exterior obstructions or window shade, and is located in State College, PA.
Figure 4-7. Raw S/E ratio distributions vs. Normalized S/E ratio distributions
The histogram in blue is the S/E ratio distribution when horizontal blinds are lowered and tilted at 45° angle. The histogram in red is the S/E ratio distribution when no shade is applied. The space is facing south with no exterior obstructions, located at State College, PA. The cosine-corrected photosensor is located 3 ft (0.9 m) deep into the room and directed 45° towards the window.

4.3.2. Statistical Analyses Procedure

The statistical analyses were conducted in three stages. The first stage analysis was conducted within each shade group. ANOVA tests were applied to identify the significant photosensor characteristics or layouts and their interactions for a specific shade setting. The response was the NDW of S/E. Systems with low variance represent good designs. Shared significant factors among all shade conditions indicate that they were independent of the shade settings and suitable for application in systems integrated with multiple shade settings, whereas the factors that only show significance with a specific type of the shade are more likely to be shade-dependent. The second stage analysis compared the median of S/E for each shade group. This part of the study focused on the shifts of the distribution across shade settings. Supplementary to the first stage, the results from the second stage identify the contributions due to different shade settings on the system performance. The third stage conducted ANOVA tests with pooled data of all the shade settings. The LightLouver cases were separately addressed due to the different model configurations. The Stage 3 results compared to Stage 1 and 2 provide comprehensive information on the importance of each factor and the photocontrol system configurations that achieve good performance.
4.4. Base Energy Performance Analysis

An energy performance evaluation was conducted to validate the research findings on the configurations that effectively reduced the variance under active shade operation and provide good photocontrol system performance.

The study case is a south-facing space with no exterior obstructions. The target illuminance was set at 400 lux. The electric lighting layout is shown in Figure 4-8. The first two rows are the dimmed zone, whereas the third row, deepest into the room, is the non-dimmed zone. Two shade operation scenarios were studied. Fabric shades with openness were controlled automatically in the first scenario. The second scenario applied daylight redirecting LightLouver with diffuse fabric shades controlled automatically for the rest of fenestration opening. The shade control algorithm limited the direct sunlight penetration (>1000 lux due to direct sunlight from the 5th phase results) to less than 4 ft (1.2 m) on the floor (IESNA 2012). The photosensors with cosine-corrected directional sensitivity directed 45° towards the window (F45) and 30° towards the back wall (B30) were compared in the first scenario. The photosensors with cosine-corrected and biquadratic-cosine corrected directional sensitivity directed straight down towards the floor (D0) and 45° towards the back wall (B45) were compared in the second scenario. The selection of these photosensors was based on the system performance analysis results. The photocontrol system applies a closed-loop linear proportional control algorithm and was calibrated based on the following criteria. The work plane illuminance was maintained above 90% of the target for 98% of the scheduled operating hours. The dimmed zone energy consumption during the dimming hours direct reflects the system response accuracy. Both the full system energy consumption for entire operation schedule and the dimmed zone energy consumption during dimming hours were compared. The results are provided in Chapter 8.
Figure 4-8. Electric lighting layout for energy performance analysis
Chapter 5 PERFORMANCE IMPACT WITHIN A SHADE GROUP

This chapter compares the performance of the photocontrol system configurations and their interactions across the environment variables when the shade was lowered at fixed positions. Figure 5-1 shows the overall performance of the photocontrol system by each shade setting in terms of NDW. When the fabric shades without openness were fully closed, the transmission of the daylight was completely diffuse. As shown, the FS_NO case was the lowest in NDW. The other six shade settings were higher in NDW. A study case with 0° horizontal blinds is provided and analyzed in detail first, followed by a summary of system performance for the six other general shade settings. The performance of the LightLouver case with fixed shade settings is also discussed at the end of this chapter.

![Main Effects Plot for NDW](image)

**Figure 5-1.** Overall performance of photocontrol system across the shade settings

5.1. System Performance with 0° Horizontal Blinds

5.1.1. Case Study

The study case is a south-facing space with exterior obstructions, located in State College, PA. The impacts of the photocontrol system configurations on the NDW are summarized in Figure 5-2. The interactions between each factor are plotted in Figure 5-3.
**Figure 5-2.** Impact of photocontrol system configuration on the NDW in the 0° horizontal blinds study case (HBlinds)

60D: cosφ-corrected with cut-off at 60°; cos4D: cos^4φ-corrected; cosD: cosφ-corrected
ANOVA test results indicate that three system configuration variables, the spatial sensitivity, the aiming direction, and the mounting distance of the photosensor from the window are statistically significant (p<0.05). Figure 5-2 illustrates that the aiming direction of the photosensor is the most important among the three factors. Directing the sensor away from the window reduces the S/E variations resulting from a view of surfaces illuminated by direct sunlight, but produce lower daylight signals across the dimming range, as illustrated in Figure 5-4, and thus may be more sensitive to changes in interior reflections, such as papers covering the top of a dark desk. The photosensor located at a 7 ft (2.1 m) depth performed better than one located at an 11 ft (3.4 m) depth when they were directed towards the back wall (See Figure 5-2). The impacts of the depth and the sensor type are relatively weak. A cosine-corrected photosensor, located deeper into the room, generally performed better across all aiming directions. Figure 5-3 investigates the interactions between the three configuration variables. The interaction between the sensor type and the sensor direction has a higher significance. As observed from Figure 5-3, the cosine-corrected photosensor with a cut-off at 60° performed better when it did not see the exterior. The cos⁴φ-corrected photosensor is also narrow in sensitivity and performed similarly to the cut-off sensor. This type of photosensor is less effective when directed towards the floor, but is less sensitive to
daylight fluctuations when directed towards the window, compared to the cut-off sensor. The cosine-corrected photosensor directed 45° towards the window and the back wall both performed better than the photosensor directed straight down towards floor. The cause of better performance when the cosine-corrected photosensor was directed 45° towards the window might relate to the higher S/E, which reduced fluctuation during the normalization process of NDW:

\[
NDW = \frac{75^{th} \text{ percentile} - 25^{th} \text{ percentile}}{\text{Median}}
\]

Figure 5-4. System Performance with a cosine-corrected photosensor directed 45° towards a window vs. 45° towards the back wall
5.1.2. Full Performance

Other than the system configurations alone, the environment variables, the sky conditions, and their interactions with the system configuration factors contribute significantly to system performance accuracy. The ANOVA model is provided in Table A-2. Figure 5-5 summarizes the main effects of the independent variables at each level. The full interactions are plotted in Figure 5-8.

The sky contributes the greatest to the S/E ratio variations. The partly cloudy condition introduces the highest variance in NDW, which was expected based on the findings from the past research reviewed in Chapter 2. Accordingly, the four site locations selected in this study are different in their climate conditions. Phoenix and State College receive a higher amount of sunshine than Seattle during the hours within the dimming range (< 200 lux at the critical point). The daylight level resulting from the lower latitude and higher amount of sunshine in Houston usually exceeds the target and does not contribute to system performance during the dimming hours, causing overcast and partly cloudy hours to drive the main system response. The photocontrol system in spaces facing south and east performed similarly in that the photosensor received a signal more frequently from reflected sunlight. The exterior obstruction ranks the third in contributions to total variance in the system response (see Table 5-1). The exterior obstruction case increased system response fluctuations (NDW) compared to a space with an unobstructed view of the horizon. Figure 5-7 compares the S/E distributions in spaces with and without the exterior obstruction. The space with exterior obstruction received lower daylight levels, has more data points, and demonstrates higher variance under partly cloudy sky conditions.

The aiming direction of the photosensor is the most significant among the three system configuration factors. The type of sensor (i.e. the sensitivity distribution) has the weakest impact. Within the system configuration variables, the interaction between the direction and the type of the photosensor has the greatest significance. The reasons are discussed in 5.1.1. Some of the interactions between the environmental variables and the system configuration factors are also statistically important and provide valuable information for system setup. The interaction between the sky and the aiming direction of the photosensor indicates that the direct sun and its penetration is a major reason why a photosensor directed towards the floor does not provide good performance. In spaces with low angle exterior obstructions, directing a photosensor towards the floor was estimated to perform worse than one directed 45° towards the window. The depth of the
photosensor in east-facing spaces is not a significant contributor to the system performance. The interaction between the sky and the depth of the photosensor directly demonstrates that daylight distribution in an interior space is determined by the sky condition. The performance improvements from a 7 ft (2.1 m) depth to an 11 ft (3.4 m) depth is less significant than those from a 3 ft (0.9 m) depth to 7 ft (2.1 m) depth (see Figure 5-6).

**Figure 5-5.** Main effects plot for NDW in spaces operated by the 0° horizontal blinds
Figure 5-6. Fisher Comparison: Interaction between Sky and Depth

Figure 5-7. S/E distributions in a space with no exterior obstruction vs one with a low angle exterior obstruction.

The space is facing south located in State College, PA. A cosine-corrected photosensor located 3 ft (0.9 m) deep into the room and directed 45° towards the window is used.
Figure 5-8. Full independent variable interaction plot for NDW in spaces with 0° horizontal blinds (HBlinds)
5.2. System Performance Comparisons across the Fixed Shade Settings

The ANOVA models are fitted individually for each shade position. The full fitted models are summarized in Appendix A and the two-way interactions were plotted in Appendix B. The fitted models explain 74% to 95% of the variance in NDW, based on R-squared values, according to the size of the data and other random errors. The predictions of the models are strong in power. The operation without a shade application has fewer hours of S/E ratios due to conditions that frequently exceed the system operation range (the critical point illuminance is often greater than 200 lux). As a result, the model explained the least variance of NDW across all cases. Table 5-1 provides the ranking of 10 significant factors and interactions for the seven general shade settings. The aiming direction of the photosensor ranked with high importance in all shade settings, except the case with the diffuse fabric shade fully closed. The high significance of the interaction between the sky conditions and the sensor aiming direction also indicates that the performance of the systems with different photosensor aiming are largely determined by the specular transmission conditions. Generally, the photosensor directed 45° towards the back wall performed the best. The impact of the photosensor mounting location ranked second in photocontrol system configurations, but the influence is significantly weaker in a system operated with fabric shades covering the upper window while leaving the lower window pane open (US_NO and US_O). In most cases, the photosensor with a cosine-corrected sensitivity (the widest field of view) performed the best. A few conditions with the cosine-corrected photosensor directed 45° towards the window delivered acceptable performance, due to the high magnitude of the signal and resulting low normalized variances. The shielded sensor with a cut-off angle at 60 degrees performs the worst and is not recommended to be used directed towards the exterior. The type of photosensor is a non-significant factor across the shade settings: 45Blinds, US_O and US_NO, but has weak significance across other shade settings. When the shades are lowered more frequently in these shade settings, the photosensor’s field of view is not a major concern. The interaction between the sensor direction and the photosensor depth, similar to the interaction between the sky and the photosensor depth discussed earlier, is statistically significant when the interior daylight level is lower, indicating that the signal magnitude is one of the important concerns for a smart system setup. The improvements from 7 ft (2.1 m) depth to 11 ft (3.4 m) depth are limited due to the inherent penalties caused by the lower signals at the 11 ft distance. Additionally, the exterior obstruction condition ranked unexpectedly high in importance across most shade settings. In the systems with the exterior obstruction, directing the photosensor...
towards the floor is generally risky for providing acceptable system performance when the shade is lowered at fixed positions.

Table 5-1. Ranking of significant factors in fitted models for each shade group (General)

<table>
<thead>
<tr>
<th></th>
<th>FWIN</th>
<th>HBLINDS</th>
<th>45BLINDS</th>
<th>US_O</th>
<th>US_NO</th>
<th>FS_O</th>
<th>FS_NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>SD</strong></td>
<td>S</td>
<td><strong>SD</strong></td>
<td>OB</td>
<td>OB</td>
<td>S</td>
<td>OR</td>
</tr>
<tr>
<td>2</td>
<td><strong>D</strong></td>
<td></td>
<td>S</td>
<td>S</td>
<td></td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>OB</td>
<td>OB</td>
<td><strong>SD</strong></td>
<td><strong>SD</strong></td>
<td>OR</td>
<td>S*OR</td>
</tr>
<tr>
<td>4</td>
<td>S*OR</td>
<td>S*OR</td>
<td>S*OR</td>
<td>S*OB</td>
<td>S*OB</td>
<td><strong>D</strong></td>
<td><strong>D</strong></td>
</tr>
<tr>
<td>5</td>
<td>OB*OR</td>
<td>S*OB</td>
<td>S*OB</td>
<td>OB*OR</td>
<td>OB*OR</td>
<td>OB</td>
<td>OR*D</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>S*C</td>
<td><strong>D</strong></td>
<td>S*SD</td>
<td><strong>SD*D</strong></td>
<td>OR*SD</td>
<td>OB</td>
</tr>
<tr>
<td>7</td>
<td>OB</td>
<td>S*SD</td>
<td>S*C</td>
<td><strong>SD*D</strong></td>
<td>S*SD</td>
<td>S*SD</td>
<td>OR*SD</td>
</tr>
<tr>
<td>8</td>
<td>S*OB</td>
<td><strong>D</strong></td>
<td>OR*C</td>
<td>OB*SD</td>
<td>OB*SD</td>
<td><strong>ST*SD</strong></td>
<td>OR<em>SD</em>D</td>
</tr>
<tr>
<td>9</td>
<td>S*SD</td>
<td>OR</td>
<td>OB*OR</td>
<td>S<em>OB</em>SD</td>
<td>OR</td>
<td>S*D</td>
<td><strong>SD</strong></td>
</tr>
<tr>
<td>10</td>
<td>OR</td>
<td>OB*OR</td>
<td>S*SD</td>
<td>S<em>OB</em>OR</td>
<td>S<em>OB</em>OR</td>
<td>S*OB</td>
<td>S*SD</td>
</tr>
<tr>
<td>R²</td>
<td>74.21%</td>
<td>88.77%</td>
<td>87.83%</td>
<td>90.33%</td>
<td>90.84%</td>
<td>94.58%</td>
<td>88.47%</td>
</tr>
</tbody>
</table>

Note:
S: sky; OB: obstruction; OR: orientation; ST: sensor type; SD: sensor direction; C: climate; D: depth

**Blue**: significant system configuration variables

**Green**: significant interactions between system configuration variables

Shaded: significant interactions between system configurations and environmental variables

The ranking of significance is based on Adj_MS, the variation between sample means.

5.3. System Performance Comparisons with LightLouver

LightLouver is an innovative daylight redirecting device with specular louvers. The interior contribution from direct sunlight was simulated using tensor-tree BSDF’s to provide high accuracy. The full ANOVA models for each shade setting in the LightLouver cases are summarized in Table A-8 and Table A-9. The primary significant factors are listed in Table 5-2.

Figure 5-9 shows the overall NDW resulting from the applications with and without a diffuse fabric shade covering the rest of the window pane. Figure 5-10 shows the impacts of the system configurations on the NDW. When daylight is admitted from the lower pane of the window, the performance of the system is close to that for other general shade setting cases. The system
performance is sensitive to the aiming direction of the photosensor, whereas the type of sensor is not statistically significant, nor are the second order interactions. However, when the diffuse fabric shades cover the rest of the window pane, the performance of the system was mainly driven by the LightLouver. In this situation, the type of sensor and the aiming direction of the photosensor starts to interact with the depth. The redirected sunlight resulting from the specular reflections deeper onto the ceiling increases the sensitivity of the performance to the type of photosensor, reducing the system performance when the photosensor is located close to the window, but improving the system performance when the photosensor is located at the mid-depth of 7 ft (2.1 m). While the cosine-corrected photosensor performed the best in the general shade settings discussed earlier in this chapter, the bi-quadratic cosine-corrected photosensor is more favorable in LightLouver applications. This phenomenon is also clearly demonstrated by the comparison between Figure 5-11 and Figure 5-12, and the interaction plots in Figure 5-13.

**Figure 5-9.** Overall performance of LightLouver integrated system with the shade settings

(a) LL_NS  
LightLouver application without shades covering the rest of the window

(b) LL_WS  
LightLouver application with fabric shades covering the rest of the window

**Figure 5-10.** Impact of photocontrol system configurations on the NDW in the system with LightLouver. Case Location: State College
**Figure 5-11.** Main effects plot for NDW in spaces operated by LL_NS

**Figure 5-12.** Main effects plot for NDW in spaces operated by LL_WS
Table 5-2. Ranking of significant factors in fitted models for each shade setting (LightLouver)

<table>
<thead>
<tr>
<th></th>
<th>LL_NS</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>Sky</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sky</td>
<td>2</td>
<td>Depth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Climate</td>
<td>3</td>
<td>SensorDir</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>4</td>
<td>Sensor Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SensorType*SensorDir</td>
<td>5</td>
<td>Sky*Climate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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Chapter 6 SYSTEM PERFORMANCE ACROSS SHADE SETTINGS

6.1. Significance of Shade Settings on System Performance
In addition to the environmental variables and the system configuration variables, Chapter 6 focuses on investigating impacts of the shade settings on system performance. The shade setting is statistically significant to the system performance based on the ANOVA test results (p=0.000 < 0.05). The importance rank of the shade settings on the NDW is higher than the type and the depth of the photosensor. The overall contributions across shade settings to the system performance are summarized in Figure 6-1. With less direct sunlight admission in the condition when the shade is fully closed, this shade condition yields a high median in S/E ratios. Figure 6-2 (a) and (b) compare the contribution of the medians in each individual shade group to the system performance integrated with multiple shade settings. When the system was configured differently, even though each shade group has similar NDW (e.g. Figure 6-2 (a) and (b)), the system configuration that resulted in a lower difference in medians (e.g. Figure 6-2 (b)) is higher in overall system response accuracy. The system that has low NDWs as well as closer medians across all shade settings, with a photosensor directed 45° towards the back wall, performed the best (e.g. Figure 6-2 (c)).

(a) Impact of shade settings on Median (General)  
(b) Impact of shade settings on NDW (General)
(c) Impact of shade settings on Median (LightLouver)  
(d) Impact of shade settings on NDW (LightLouver)

**Figure 6-1.** Overall impact of shade settings on system performance

(a) S/E ratio distributions with the photosensor directed 45° towards the window  
NDW=0.512 Median=2.563 N_Median_std=0.232
(b) S/E ratio distributions with the photosensor directed towards floor
NDW=0.282 Median=1.334 N_Median_std=0.156

(c) S/E ratio distributions with the photosensor directed 45° towards the back wall
NDW=0.227 Median=0.596 N_Median_std=0.131

Figure 6-2. S/E ratio distribution comparison for systems integrated with multiple shade settings
The space is facing south with no exterior obstruction, and is located in Houston, TX. Cosine-corrected photosensors located 7 ft (2.1 m) deep into the room are used.
6.2. Performance of the Photocontrol System across Shade Settings

6.2.1. System Performance across Shade Settings

The ANOVA model fitted for NDW with the pooled data is summarized in Table C-2. The fitted model for the normalized standard deviation of the S/E ratio medians (N_Median_std), as a supplement to how the shade settings contribute to the overall photocontrol system performance, is summarized in Table C-1. The main effects of the environmental and system configuration variables for N_Median_std and NDW are plotted in Figure 6-3 and Figure 6-4, respectively. The full independent variable interactions for NDW are plotted in Figure 6-5. The rank of importance for the variables and their interactions is listed in Table 6-1. Though all independent variables remain statistically significant, the patterns of impacts and their interactions are different from the system with a fixed shade setting. Based on the statistical analysis results, the environment variables do not impact the system integrated with multiple shade settings as significantly as on a system fixed at a single shade setting. The exterior obstruction that caused significant increases in NDW in a system with a fixed shade setting resulted in a slight reduction in NDW in a system integrated with multiple shade settings. The clear sky and overcast sky contributed the opposite to the NDW in a system integrated with multiple shade settings, compared to the NDW in a system with a fixed shade setting. The plots in Figure 6-6 explain the reason. The amount of data for a clear sky is less due to the high daylight levels across most clear sky hours. The NDW for each shade setting in the overcast condition (see Figure 6-6 (b)) is smaller in value, but the medians of the S/E ratios across different shade settings are largely different. On the contrary, the NDW for each shade setting under a clear sky condition (see Figure 6-6 (a)) is larger in value, but the medians of the S/E ratios for each shade setting are closer to each other. The closer medians of S/E ratio across different shade settings are the primary reason for the better performance. The system performance caused by the system configuration variables did not change. The direction of the photosensor remains the highest in importance, and the type of photosensor is the least in importance. The depth and its interactions increased in importance in a system integrated with multiple shade settings. The NDW and N_Median_std were both reduced in a system with the photosensor located deeper into the space.
Figure 6-3. Main effects plot for NDW in spaces across shade settings

Figure 6-4. Main effects plot for the standard deviation of the Median across shade settings
Compared to the system operated at the fixed shade positions, the systems integrated with multiple shade settings were more sensitive to the interactions between the aiming direction and the location of the photosensor (see Table 6-1). The interaction term indicates that the sensor located at a 3 ft (0.9 m) depth performed significantly worse than the sensor located at a 7 ft (2.1 m) depth, but the improvements from 7 ft (2.1 m) to 11 ft (3.4 m) were less.
(a) Clear Sky S/E ratio distribution in system integrated with multiple shade settings
(N_Median_std=0.229)

(b) Overcast Sky S/E ratio distributions in a system integrated with multiple shade settings
(N_Median_std=0.294)

Figure 6-6. S/E ratio distribution comparisons by sky condition in systems integrated with multiple shade settings.
The space is facing south with no exterior obstruction, located in Houston, TX. The cosine-corrected photosensor directed 45° towards the window and located 7 ft (2.1 m) deep into the room is used.
6.2.2. LightLouver System Performance across Shade Settings

The fitted ANOVA models for LightLouver system performance across shade settings are summarized in Table C-3 and Table C-4. The full two-way interactions were plotted in Error! Reference source not found. The main effects of the environmental and system configuration variables for N_Median_std and NDW are plotted in Figure 6-7 and Figure 6-8, respectively. The rank of importance for the variables and their interactions is listed in Table 6-1. The overall performance patterns are similar to the system performance across the general shade settings. The major differences are that the type of photosensor and its interactions became increasingly important. This could be explained by the reflected sunlight onto the ceiling by the LightLouver. A photosensor with a cosine-corrected sensitivity receives large specular reflections and performed the worst when located closer to the window. The interaction between the photosensor aiming direction and the depth indicates that a deeper photosensor directed towards the back wall does not provide better system performance. As discussed in 5.3, the photosensor located at a 7 ft (2.1 m) depth received more signal from daylight and is the preferred choice to deliver good system performance.

![Main Effects Plot for NDW](image)

*Figure 6-7 Main effects plot for NDW across shade settings (LightLouver)*
Figure 6-8. Main effects plot for the standard deviation of the Median across the shade settings (LightLouver)

Figure 6-9. Full independent variable interaction plot for NDW across shade settings (LightLouver)
Table 6-1. Ranking of Significant Factors in Fitted Models for system integrated with multiple shade settings

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<tr>
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<td>SD</td>
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<tr>
<td>2</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>SD*D</td>
</tr>
<tr>
<td>4</td>
<td>OB*SD</td>
</tr>
<tr>
<td>5</td>
<td>S</td>
</tr>
<tr>
<td>6</td>
<td>OR</td>
</tr>
<tr>
<td>7</td>
<td>ST</td>
</tr>
<tr>
<td>8</td>
<td>S<em>SD</em>D</td>
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<td>9</td>
<td>OB</td>
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<tr>
<td>10</td>
<td>S*D</td>
</tr>
<tr>
<td>R²</td>
<td>91.53%</td>
</tr>
</tbody>
</table>

Note:
- S: sky; OB: obstruction; OR: orientation; ST: sensor type; SD: sensor direction; C: climate; D: depth
- **Blue**: significant system configuration variables
- **Green**: significant interactions between system configuration variables
- **Shaded**: significant interactions between system configurations and environmental variables
The ranking of the significance is based on Adj_MS, the variation between sample means.
Chapter 7  SYSTEM PERFORMANCE SENSITIVITY TO AIMING DIRECTION

The results in Chapter 5 and Chapter 6 indicate that the direction of the photosensor plays the most important role among the investigated system configuration variables in providing good system performance. The photosensor facing away from the window provided the best performance. Additionally, the results show that improvements for the deepest photosensor (11 ft / 3.4 m), compared to the photosensor located at 7 ft (2.1 m) depth, are limited. The reason was considered to be the lower daylight signal available. The type of photosensor yields the lowest influence with a slight preference towards the cosine-corrected sensitivity in system integrated with multiple shade settings. The cosine-corrected photosensor receives daylight from all directions, is usually higher in signal, and was found to deliver good system performance when located deeper. The study in this Chapter added additional aiming angles of 15° and 30° towards the back wall into the model. The results are summarized in Figure 7-1 and Figure 7-2. Based on the results, the cosine-corrected photosensors directed towards the back wall were confirmed to perform better than photosensors with other aiming directions. Generally, the greater the angle towards the back wall, the smaller the NDW and N_Median_std due to the more limited direct view of the exterior. To look into the improvements by tilt angles, the results for the State College, PA cases are plotted in Figure 7-3. The B15 photosensor located at a 3 ft (0.9 m) depth did not perform well. Except for this specific system configuration, the photosensors with an aiming angle towards the back wall all delivered high quality performance that were close to each other. Figure 7-4 plots the S/E ratios with a cosine-corrected photosensor directed 15° towards the back wall (B15) in a system integrated with multiple shade settings. Compared to Figure 6-6 (c), which plots the S/E ratios with a photosensor directed 45° towards the back wall (B45), the B15 photosensor has a lower NDW and identical N_Median_std. The median S/E ratio (0.952) of a B15 photosensor is significantly higher than that of a B45 photosensor (0.585). It means that with the same work plane critical point illuminance, the B15 photosensor receives about twice as much signal as the B45 photosensor. The abundant signal will improve system performance in a real condition by providing a larger dimming signal range and reducing the sensitivity of the photosensor to variations in interior reflectance.
**Figure 7-1.** Main effects plot for N_Median_std across shade settings (focus: the direction of the photosensor)

**Figure 7-2.** Main effects plot for NDW across shade settings (focus: the direction of the photosensor)
Figure 7-3. Impact of photocontrol system configurations on the NDW (additional SD)
State College data are selected for this plot

Figure 7-4. S/E ratio distributions in systems integrated with multiple shade settings (B15 Sensor Direction) NDW=0.179 Median=0.953 N_Median_std=0.135
The space is facing south with no exterior obstruction, located in Houston, TX. The cosine-corrected photosensor directed 15° towards back wall, located 7 ft (2.1 m) deep into the room is used.
Chapter 8 SYSTEM ENERGY PERFORMANCE WITH AUTOMATED FABRIC SHADES

The energy consumption in an automated shading system is a direct indicator of the photocontrol system’s performance and was calculated to validate the research findings in Chapter 5, Chapter 6 and Chapter 7. The energy performance was based on a system calibration that limited over-dimming to no more than 2% of time. Figure 8-1 and Figure 8-2 summarize the relationships between NDW and energy performance with different system configurations in the two scenarios with automated shades. The system with smaller NDW performed better and consumed less energy as predicted in Chapter 6. In the basic shading device scenario, a photosensor directed 45° towards the window (F45) at a 3 ft (0.9 m) depth (NDW=0.669) is a configuration used by some manufacturers to represent an open-loop photosensor. The photosensor directed 45° towards the window results in a significant amount of overshooting when overdimming was limited to 2% of the hours. The system with a B30 photosensor located 7 ft (2.1 m) deep into the room (NDW=0.238) consumes approximately 10% less system energy and 31% less dimmed zone energy than the 3 ft (0.9 m) F45 photosensor. The improvements in system energy savings and dimmed zone energy savings for an 11 ft (3.4 m) B30 photosensor (NDW=0.198) over the 7 ft (2.1 m) B30 photosensor are 1% and 3%. A deeper photosensor location at 11 ft (3.4 m) has limited improvements on both the response accuracy and the energy savings.

In the LightLouver scenario, generally, the results highly align with performance prediction using NDW. A narrower photosensor directed towards the back wall performed the best with no depth preference. Locating a cosine-corrected photosensor directed straight down deeper inter the space improved the system performance. The system with lower NDW is lower in system energy consumption. The energy performance case study results validate the research findings that directing a photosensor away from the window improves the performance of a system with active shade operation. A medium depth (7 ft / 2.1 m) should be sufficient to achieve good performance.
Figure 8-1. Energy consumption in comparison to an undimmed system for different system configurations vs. NDW. The space is facing south with no exterior obstructions and is located in State College, PA. Cosine-corrected photosensors are used. 3650 occupancy hours were used in the system energy savings calculations. The shades were open for 2222/3650 hours; the upper pane was shaded for 675/3650 hours; and the shades were fully closed for 753/3650 hours. Two-thirds of the luminaires are in the dimmed zone. For 1738 hours, the critical point illuminance from daylight exceeds the target and the system was shut off. 1912 hours, in total, require electric light.
Figure 8-2. Energy performance for different system configurations vs. NDW (LightLouver)
The space is facing south with no exterior obstructions, located in State College, PA. Cosine-corrected and biquadratic-cosine corrected photosensors are used. 3650 occupancy hours were used in system energy saving calculations. The shades were open for 2198/3650 hours; the shades were fully closed for 776/3650 hours. Two-thirds of the luminaires are in the dimmed zone. For 2074 hours, the critical point illuminance from daylight exceeds the target and the system was shut off. 1576 hours in total require electric light.
Chapter 9 CONCLUSIONS

9.1. Research Findings
This dissertation examined performance differences between photocontrol systems with a fixed shade setting and when applied across multiple shade settings. The impact of the environmental variables and system configuration on system performance were analyzed based on fitted ANOVA models.

The research aimed to answer the following questions:
1. Do shade settings impact photocontrol system performance?
2. How do sky conditions contribute to the photocontrol system performance across shade settings?
3. Do the direction, type, and the depth of a photosensor impact the photocontrol system when integrated with multiple shade settings? Which one is the most important and what is the best photosensor arrangement?
4. Are interactions of independent variables (related to both system configuration and the environmental variables) important to system performance?

To illustrate the performance differences in photocontrol systems with a fixed setting and integrated across multiple shade settings, and to provide more comprehensive applicable system configuration strategies in real spaces (considering active shade operation with multiple settings), this study compared the contributions of environmental and system configuration variables in systems with a fixed shade setting to those integrated with multiple shade settings. The results lead to the following conclusions:

- **Fixed shade setting:**
  - The sky conditions and low-angle obstructions introduce significant variance in interior daylight distributions and are statistically significant contributors to the photocontrol system performance (variance in S/E ratios). Clear and partly cloudy sky conditions and the presence of low altitude angle exterior obstructions produce higher variations in S/E ratios.
  - The aiming direction of the photosensor ranks the highest among system configuration factors in providing good system performance. A photosensor
directed 45° towards the back wall provides the best performance under most conditions.

- The interaction between the aiming direction of the photosensor and the presence of exterior obstructions indicates that a photosensor aimed towards the floor (straight down) provides the worst performance.

- The statistical interaction between the sky conditions and the direction of the photosensor explains the primary reason for high importance of photosensor direction.

- The photosensor’s field of view has less impact on system performance. The directional sensitivity of a photosensor is not statistically important in shade settings with horizontal blinds tilted at 45 degree angles, and diffuse fabric shades or shades with openness covering partial window. A cosine-corrected photosensor is generally preferred to provide a higher daylight signal and more accurate response under the other four shade settings.

- The mounting distance of the photosensor from the window was a statistically significant factor in the system performance for most shade settings except for fabric shade cases with the lower window pane left open (US_NO and US_O). A deeper photosensor location generally provides a lower total response variance. The interactions between the depth of the photosensor and the direction of the photosensor, however, caused limited improvements when the photosensor is directed towards the back wall and located deep within the space (11 ft / 3.4 m) compared to the same photosensor located at mid-depth (7 ft / 2.1 m). The deep photosensor position receives a low daylight signal.

- The contribution of the environmental variables and the photocontrol configuration variables to the overall performance of a photocontrolled system with a LightLouver sunlight redirection device on the upper window was close to that with other shade settings. The major differences are:
  - The cosine-corrected photosensor performed the worst, since it receives more specular reflections from the LightLouver.
  - When the interior daylight was dominated by LightLouver, with shades covering the rest of the window pane, the photosensor located at a 7 ft (2.1 m) depth is highly preferred due to a lower signal from specularly reflected sunlight compared to a photosensor located at a 3 ft (0.9 m)
depth, and provides a much higher signal compared to a 11 ft (3.4 m) depth sensor.

- Multiple shade settings:
  o The shade setting is a statistically significant factor in system performance. Its importance ranks high.
  o The environmental variables (sky conditions, exterior obstructions, orientation, and geographical site) were less significant in system performance across multiple shade settings, compared to a system with a fixed shade setting.
    - The variance in S/E ratio medians across the shade settings was lower in the clear sky condition and partly cloudy condition compared to the overcast condition. This phenomenon caused unexpected better system performance under clear sky conditions, compared to the overcast sky conditions, when the shades were operated.
    - The climate of the geographical sites was not of great importance to the system’s response. A system designed for a northern climate can be applied to a southern climate without a great change in performance.
  o The system configurations contribute higher to the S/E variance when the shade settings are permitted to vary. The direction and the depth of the photosensor and the interactions strongly affect the system performance. The directional sensitivity of the photosensor, which is less important to the photocontrol system performance with a fixed shade setting, increases in importance.
    - Directing a photosensor towards the back wall improves system performance
      - A greater tilt angle results in less variance in S/E ratios, but also reduces the daylight signal. A comparison between photosensors directed 15° (B15), 30° (B30) and 45° (B45) toward the back wall indicates these sensors perform similar to each other when located deeper than 3 ft (0.9 m), but the received signals from daylight for the B15 and B30 photosensors are significantly higher.
      - A photosensor located at a 7 ft (2.1 m) depth performed well and receives a higher signal from daylight compared to a photosensor located at an 11 ft (3.4 m) depth.
- The photosensor with a cosine-corrected photosensor was preferred in a system operated with most shade settings, but performed worst in the LightLouver cases.

An energy performance study was conducted to validate the research findings in this study. The systems with lower NDW in the basic shading device scenario show a reduction of 5.3% system energy consumption and, in the LightLouver scenario, the proper system configuration with low NDW decreased 20.3% total energy consumption.

Based on the results of this study, the design of photocontrol system in spaces with less frequent shade operation requires attention to the exterior obstruction and the sky conditions. A direct view of the exterior may significantly reduce system response accuracy. The design of the photocontrol system in spaces with automated shading or more frequent shade operation should pay more attention to the variance in S/E ratios introduced by different settings of the shade. Here, the system configuration (layout) is of great importance to system performance. Generally, an open-loop photosensor located closer to the window and directed towards the exterior will not provide acceptable system performance. The photosensor directed at 15° or 30° towards the back of the space located at a mid-depth within the daylight zone can receive a sufficient daylight signal, provide accurate system performance, and save reasonable energy. If the daylight delivery system is not primarily operating with specular reflections, the type of photosensor is not significant. When specular reflections are present, designers should try to avoid a photosensor with a wide sensitivity distribution.

The statistical analysis procedure applied in this study demonstrates high efficiency in providing valuable information on the photocontrol system setup, based on the parametric model simulation results.

9.2. Limitations and Future Work

Interior daylight distributions result from complex combinations of daylight delivery system designs (e.g. window aperture size, transmittance, exterior shading devices, etc.) and the exterior surround (e.g. snow, trees, specular reflections from the windows of a nearby building, etc.). Study cases were modelled with uniform material properties, symmetric geometry, and a simple exterior surround to remove unnecessary biases. Variations in the room properties may introduce
different performance patterns that are not addressed in these study cases. Systems that apply highly directional photosensor spatial distributions may also require more detailed simulations and mock-ups.

The computer model study space is a medium size classroom with high energy savings potential. It should provide good reference power to the photocontrol system performance in building sectors of similar types and dimensions. Further study would be necessary to validate the application of the recommendations of this research to other spaces.

Spectrum changes during the daylight hours, as well as spectrally selective (i.e., chromatic) reflection or transmission, were not considered.

Regarding the statistical modeling approaches used in this work, the distributions of the S/E ratios are highly skewed due to the nature of daylight, environmental variables and the system configurations. The median and the percentile values were used to quantify the distribution statistics. Kruskal-Wallis non-parametric tests were conducted for each main factor in the tested model to verify the significance of conclusions. All main factors were statistically significant. In the process of the statistical analysis, the ANOVA models assume normally distributed and equal variance residuals with a mean of 0. The fitted models for the general type shade settings, though with a few outliers, all passed the error assumptions. The LightLouver cases required Box-Cox transformations before fitting the models. The residual plots had fewer outliers and a distribution closer to a standard normal after the transformation. The model for N_Median_std in the LightLouver cases for the across shade settings model yields a 1.8% lack of fit, but may not affect the general conclusions of factor importance.
## Appendix A. ANOVA MODELS FOR EACH SHADE GROUP

**Table A-1. ANOVA model: No Shade (FWin)**

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### Analysis of Variance

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### Model Summary

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Table A-2. ANOVA model: 0° Horizontal Blinds (HBlinds)

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Analysis of Variance

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Table A-4. ANOVA model: Fabric shades with openness covered upper windows (US_O)

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Table A-5. ANOVA model: Fabric shades without openness covered upper window (US_O)

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Table A-6. ANOVA model: Fabric shades with openness covered whole window (FS_O)

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Model Summary

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<th>R-sq(pred)</th>
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<td>90.84%</td>
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Table A-7. ANOVA model: Fabric shades without openness covered whole window (FS_NO)

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<td>Clear, Overcast, PartlyCloudy</td>
</tr>
<tr>
<td>Obstruction</td>
<td>Fixed</td>
<td>nobs, obs</td>
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<td>Orientation</td>
<td>Fixed</td>
<td>East, North, South</td>
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<td>60D, cos4D, cosD</td>
</tr>
<tr>
<td>SensorDir</td>
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<td>b45, d0, f45</td>
</tr>
<tr>
<td>Climate</td>
<td>Fixed</td>
<td>Houston, Phoenix, Seattle, StateCollege</td>
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Analysis of Variance

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Table A-8. ANOVA model: LightLouver applications without fabric shades covering the rest of the window pane (LL_NS)

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<td>Depth</td>
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| Error | 185 | 58.010 | 0.3136 |

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Table A-9. ANOVA model: LightLouver applications with fabric shades covering the rest of the window pane (LL_WS)

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<tr>
<td>SensorDir</td>
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<td>b45, d0</td>
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Analysis of Variance

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Error                      | 152 | 12.443   | 0.0819  |
Total                      | 215 | 250.345  |

Model Summary

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Appendix B. FULL INTERACTION PLOTS FOR EACH SHADE GROUP

Figure B-1. Full independent variable interaction plot for NDW in spaces with FWin
Figure B-2. Full independent variable interaction plot for NDW in spaces with 45Blinds
Figure B-3. Full independent variable interaction plot for NDW in spaces with US_NO
Figure B-4. Full independent variable interaction plot for NDW in spaces with US_O
Figure B-5. Full independent variable interaction plot for NDW in spaces with FS_NO
Figure B-6. Full independent variable interaction plot for NDW in spaces with FS_O
Figure B-7. Full independent variable interaction plot for NDW in spaces with LL_NS
## Appendix C. ANOVA MODELS FOR EACH SHADE GROUP

### Table C-1. ANOVA model: Normalized Standard deviations of the Median across the shade settings (General)

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<th>Values</th>
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</tr>
<tr>
<td>Obstruction</td>
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<td>Fixed</td>
<td>3 East, North, South</td>
<td></td>
</tr>
<tr>
<td>SensorType</td>
<td>Fixed</td>
<td>3 60D, cos4D, cosD</td>
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<td>SensorDir</td>
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<tr>
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### Model Summary

- **R-sq:** 91.53%
- **R-sq(adj):** 90.50%
- **R-sq(pred):** 89.29%

---

- **SensorType**
- **SensorDir**
- **Depth**

- **Error:**
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  - Adj SS: 1.6954
  - Adj MS: 0.00102

- **Total:**
  - SS: 1862
  - Adj SS: 20.0115
Sky*SensorDir*Depth 8 2.8529 0.3566 87.66 0.000
Obstruction*Orientation*SensorDir 4 0.0791 0.0198 4.86 0.001
Obstruction*SensorType*SensorDir 4 1.3456 0.3364 82.69 0.000
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Orientation*SensorType*SensorDir 8 0.6387 0.0798 19.62 0.000
Orientation*SensorType*Depth 8 0.1083 0.0135 3.33 0.001
Orientation*SensorDir*Climate 12 0.1085 0.0090 2.22 0.009
Orientation*SensorDir*Depth 8 0.5236 0.0654 16.09 0.000
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Error 1713 6.9690 0.0041
Total 1943 99.3386

Model Summary

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Model Summary

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### Table C-4. ANOVA model: NDW across the shade settings (LightLouver)

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<td>85.40%</td>
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VITA

Ling Chen

Ling Chen was born and grew up in Shanghai, China, where she received her early education and life experience. She likes science and engineering since she was young. She was introduced to lighting when she started her undergraduate education. In 2011, she received her Bachelor’s degree in the Department of Illuminating Engineering & Light Sources from Fudan University.

In 2011, Ling started her graduate student life in Architectural Engineering Department, The Pennsylvania State University. During her master’s study, she was introduced to the daylighting research and building sustainability by Dr. Mistrick, her academic advisor. She served as a research assistant in daylighting area under the supervision of Dr. Mistrick. Taking the advice from Dr. Houser, the lighting area committee member of her graduate study, she started to get more involvements in statistical analysis.

In 2013, Ling earned her Master’s degree from Penn State AE department in lighting option and started her new life in Doctorate study. During Doctorate study, Ling had deeper understanding about the daylighting and photocontrol system. As a research assistant, she worked on projects involving advanced daylighting simulations and simulation software developments. She is also minor in Statistics for her Doctorate study. Knowledge in statistics helped her to conduct efficient analysis and improved her research reliability.

Ling is also a LEED Green Associate and Intern Lighting Certified by the National Council for the qualification of the lighting Professionals (NCQLP).