A Framework to Support the Development of Manually Adjustable Light Shelf Technologies

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Environmental Design and Planning

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07 May, 2014
Blacksburg, Virginia

Keywords: Light Shelf, Daylight Harvesting, Framework Development.

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ABSTRACT

Active daylight harvesting technologies that are currently available in the market have often suffered from wide-spread market acceptability due to their high cost and imperfect performance. Passive systems, though simple and affordable, typically cannot harvest higher potentials of daylight, which is dynamic over days, months, and seasons, due to their static nature. There is a research and market gap that calls for investigation towards the development of low-tech, manually adjustable, high-performance daylighting mechanisms to be used as an alternative to active daylighting solutions, which are often controlled by building automation systems. This research proposes a framework to support the development of daylight harvesting mechanisms, which will allow for low-tech yet temporary adjustable systems, merging some of the advantages of active systems with passive ones. The hybrid of the above two categories will be a manually adjustable light harvesting device that will allow for quick adjustment through mechanical means to few predefined positions. These positions will be customized to each location to achieve optimum daylight harvesting. The resulting device will allow for flexible adjustment to daily and seasonal variations of the sun's path, while retaining a level of simplicity and elegance towards low-cost installation and operation.

Significant effort was made in the initial phase of this research to use experimental studies as the primary method of investigation. However, given the nature of daylight and practical constraints in the field, the experimental method was found to be not productive enough for extent of this research. As a result, simulation studies were ultimately used to generate the necessary data for the development of this framework. For the simulation phase 'DIVA4Rhino,' a climate-based daylighting software and 'Grasshopper,' a graphical programming tool for Rhino, was used to first construct a parametric simulation loop. Next, a reduced set of parameters for a manually adjustable light shelf system were tested for daylight performance, as a 'proof of concept'. Finally, based on the previous two steps, a framework to help the development of manually adjustable light shelf systems has been defined.

This research shows that light shelves, even when kept fixed at a single optimum configuration for the whole year, can increase interior daylight performance in most locations and orientations. It also shows that indoor daylight harvesting can be further enhanced if the light shelf is manually adjusted on a seasonal basis. Amongst the variations tested, rotational adjustability has been found to contribute most to the increase in performance. Segmented adjustability, e.g. where the inner and outer sections of a light shelf are manipulated separately, was found to extend performance of light shelves even further though not by significant amounts.

Acknowledgements

My committee chair, Dr. Georg Reichard, has been with me every step of the way in this long journey towards a PhD. I am indebted to him for the many thought provoking questions, constructive criticism, and invaluable assistance he has provided me throughout this arduous process. I am grateful to my committee members Dr. Yvan Beliveau and Dr. Sean McGinnis, who have enriched this path of learning for me with their many insightful thoughts and comments. Committee member Bob Schubert deserves special mention. He has been an invaluable sounding board for me throughout this endeavor and an inspiration ever since I took my first course with him, 30-years back, as a student of M.Arch at Virginia Tech.

I am grateful to Professor Dale Brentrup and his colleague Benjamin Futrell at the University of North Carolina at Charlotte (UNCC) for allowing me to use their daylighting facilities for this research. I would like to thank the people at the Laboratory for Interdisciplinary Statistical Analysis (LISA) program at Virginia Tech for their help with the statistical analysis part of this research. Thanks are also due to Dr. Ron Gibbons and Jason Meyer at the Virginia Tech Transportation Institute (VTTI) for their help with advice and equipment in this research. Numerous individuals and user groups on the World Wide Web were very generous with their time and expertise when I got stuck with technical matters and did not know how to move forward. Of special help to me were the people at the 'Performance and Form' (http://performance-and-form.com/), 'Diva for Rhino' (http://diva4rhino.com/), Designalyze' (http://www.designalyze.com/taxonomy/term/30. and the 'Excel Forum' (http://www.excelforum.com/)

This research could not have been possible without the tremendous sacrifice and patience from my wife and five kids. They put up with whatever it took so that I could achieve the goal I had set for myself. I consider this work to be as much an achievement of theirs as mine.

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Chapter 1. Introduction

1.1 Overview

Daylighting systems are traditionally divided into two basic categories: (a) Active Daylighting Systems and (b) Passive Daylighting Systems. In *active systems* there is always a typically electronic mechanism of tracking the sun either using photo sensors or an algorithm that predicts the position of the sun for a given location and date. *Passive systems*, on the other hand, are stationary devices that do not have any mechanism to actively track the sun.

The efficiency of active systems tends to be greater because the light harvesting mechanism is adjusting itself over time to face the source of energy – the sun. However, they also tend to be much more expensive to install and operate compared to their counterparts. Passive systems, being stationary, have fewer components to fail or break and thus are not only less expensive to purchase and install, but also to operate over a buildings life-time. However, in redirecting light from a moving energy source such as the sun, their stationary design becomes inherently less efficient compared to the active type.

There is a research and market gap that calls for investigation towards the development of manually adjustable, low-tech, high-performance daylighting mechanisms to be used as an alternative to active daylighting solutions, which are often controlled by building automation systems. The *hybrid* of the above two categories is a manually adjustable light harvesting device that allows for quick adjustment through mechanical means to certain predefined optimized positions derived for its particular application and point of use. This allows for flexible adjustment to variations of the sun's path in daily and seasonal cycles, while retaining a level of simplicity and elegance towards low-cost installation and operation, due to minimal maintenance needs. The proposed research investigates possible hybrid systems and formulates a framework of related parameters that are required to develop and configure such systems.

In order to establish the validity of the 'research gap' claimed above, an initial literature search was carried out to document what has been done so far and to clarify the original contribution this research attempts to make in the field of daylight harvesting systems.

1.2 Background

Daylighting strategies such as light shelves have been in use since the time of the Egyptian Pharaohs to utilize daylight indoors more effectively (Christoffersen, 1995; P.

Littlefair, 1996). Until some 75 to 100 years ago, daylighting design was much more integrated with building design than is currently the case (Benton, 1990). The availability of cheap energy, allowing ubiquitous electric lighting, and the invention of air-conditioning, which led to the de-emphasis of natural ventilation, subsequently produced large foot-print design for commercial buildings where daylighting was overlooked. Thus, some researchers argue that, despite significant innovation in glazing technologies and construction tools in recent years, daylighting design has regressed rather that advanced from where it was a century ago (Turnbull & Loisos, 2000).

The energy crisis of the 70's and emphasis on sustainability in recent times has created renewed interest in daylighting of buildings. However, there is a shortage of tools that can help the building professionals incorporate daylighting strategies into their design. This is partially because daylighting, in order to be effective, has to integrate with many other aspects of a building design. According to some experts our every-day experience with daylight may trick us to think good daylighting design to be easy. In reality, as daylighting is one of the most interdependent functions in a building, its design needs to be carefully synchronized with all other building systems to make it successful. (Heschong, 2012).

1.3 Motivation for this research

Between the performance benefits of sophisticated computer controlled daylighting systems and the simplicity of static daylighting solutions there remains a significant research gap for manually adjustable daylighting solutions. These solutions can capture higher levels of efficiency by providing specific, locally optimized adjustment mechanisms. They can also offer low installation, operation, and maintenance cost, thus providing a faster return on investment. There is historical evidence for such mechanisms, which lost their popularity with the development of cheap electricity and widespread use of air-conditioning systems. There is an opportunity to reevaluate such examples using modern analysis and assessment techniques. One can thereby develop manually adjustable

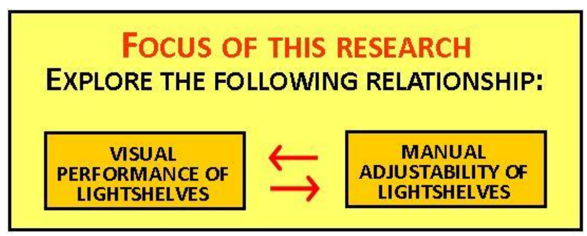


Fig. 1 Research focus: manual adjustability of light shelves.

daylighting systems that take the best of the old and improve it to create appropriate solutions for today's context.

1.4 Research Questions

This research attempts to develop a framework that would support the development of a particular type of daylighting strategy: manually adjustable light shelves. For centuries light shelves have been used in buildings to redirect daylight into the interior space. This ancient daylighting technique has been revisited in this research to:

- Quantify its performance advantages in empirical terms using recently developed analysis tools towards the goal of evidence based design.
- Explore the possibility of enhancing the performance of the traditional fixed light shelf with a newly proposed adjustable system.
- Investigate if performance improvements can be achieved even with limited adjustability of a few variables that can be operated manually by a regular user or building personnel using simple tools.

The study of manually adjustable light shelf systems encompasses many steps in research and development. This research explores in particular the relationship between the visual performance of light shelves and how it is affected by incorporating manual adjustability in them (Fig. 1). In pursuing this aim this research tries to build a 'proof of concept' by answering some fundamental questions related to adjustable light shelves, including:

- Do light shelves make any difference in interior illumination level?
- Does adjustability improve light shelf performance?
- What effect does the rate and range of any adjustments have on performance?
- Which parameters of a light shelf configuration, when made adjustable, yield the highest performance gains?
- How is light shelf performance affected by orientation and location of a building?

The goal of this research is to formulate a *generic framework* that will assist manufacturers of daylighting technologies in the development of low-cost, manually adjustable daylighting systems that can achieve higher levels of efficiency through knowledge-based configuration opportunities. The framework will further assist manufacturers to develop adaptive user manuals and applications that can be provided to the end user for efficiency optimization in a specific local context.

Chapter 2. Literature Review

The mere opening in a wall, or even the mouth of a cave for a cave dweller, can be considered a daylighting strategy. However, since those historical beginnings, daylighting systems and components have come a long way to include sophisticated mechanisms that can 'pipe' daylight many stories underground or into the center of high-rise buildings with deep floor-plates.

Beginning in 1995, Johnsen carried out an extensive research study under the Solar Heating & Cooling Programme of the International Energy Agency (IEA), a comprehensive collaborative research effort titled IEA Task 21. This effort involved more than 40 institutions from 16 IEA countries and focused on research involving innovative daylighting systems, lighting controls, and development of daylighting design tools (Johnsen, 2000). Its aim was to 'establish procedures for the characterization and evaluation of daylighting and lighting control systems performance under the very diverse nature of sky conditions throughout the world'.

The simplest and often the most effective daylighting strategy have to do with the basic building itself. External features would include the orientation, shape, spacing and opening design of the building. Internal features influencing daylighting would include reflectivity, opacity, height, and arrangement of internal surfaces and furnishing of a building. Next in priority are architectural features that are added to a building but are of permanent nature such as light shelves and sun-shades. The following section lists some of these design elements and cites existing research discussing their relationship to daylighting.

Proper **solar orientation** is the single most important factor to ensure good daylight in building interiors. For example, Kruger and Dorigo have used computer simulation for daylighting analysis of school building design in Parana, Brazil for various solar orientations (Krüger & Dorigo, 2008). This has helped designers arrive at the best placement for their buildings, considering site context and quality of interior spaces.

Buildings designed and built before the era of cheap electricity and air conditioning often had shallow floor-plates to allow daylighting reach into a majority of its spaces. Buildings with large floor-plate design can benefit from such a strategy if **light wells** of appropriate size and location can be introduced into the floor plan. Kristl and Krainer investigated the daylighting potential of light wells for multi-story apartment buildings using scale models and an artificial sky, and found best results with light wells with a wider upper and narrower lower part (Kristl & Krainer, 1999). Calcagni and Paroncini have looked at the potential of **atrium spaces** as a source of daylight for adjoining spaces (Calcagni & Paroncini, 2004). The shape, orientation, transmittance of the roof, the reflectivity of the atrium surfaces and glazed areas are some of the parameters that have been looked at in this study using Radiance as the simulation tool. The aim has been to develop a methodology for predicting the daylight levels at atrium floors and its surrounding spaces. Calcagni and others have reported on the analysis of atrium spaces for daylighting in an earlier publication (Calcagni, Filippetti, & Paroncini, 2000). Tsangrassoulis and Bourdakis have attempted comparison of daylight level prediction in atrium spaces using practical design procedures and computer simulation (Tsangrassoulis & Bourdakis, 2003). Littlefair has presented a review of current literature on daylighting design for atria that touches upon daylight prediction methods in such spaces as well (P. Littlefair, 2002). The effect of surfaces enclosing an atria, on its daylighting potential, has been studied by Cole using large scale models (Cole, 1990). It is found that floor reflectance and the proportion of openings in walls surrounding an atrium plays a significant role in daylighting the atria and its surrounding spaces. Du and Sharples have also looked at the impact of well geometries and reflectivity of interior surfaces in atria of buildings on their daylighting potential under overcast skies (Du & Sharples, 2010).

In dense urban areas window openings are often faced with **opposing facades** of neighboring buildings, which, in the right context, can be a valuable source for externally reflected daylight rather than an obstruction to daylighting. Wa-Gichia has investigated such urban facades as a potential passive daylighting strategy by using computer simulation and found promising results for certain contexts (Wa-Gichia, 1998). However, the walkie-talkie building in the UK or the art museum in Texas are recent examples of harmful reflection from opposing facades in the urban context. Therefore, to be successful, such daylighting strategies need careful integration with their surrounding built-form.

The effect of fitting windows with **sun-shades** has been studied by Ho and others in the context of classrooms in Taiwan using simulation validated by experimental observation. Results show improvement in interior lighting quantity and quality while reducing electric power cost if appropriately designed sun-shades are installed (Ho, Chiang, Chou, Chang, & Lee, 2008).

The impact of **ceiling geometry** on the performance of louvers as a daylighting strategy was investigated by Freewan and others using physical model experiments and simulation with Radiance software (Freewan, Shao, & Riffat, 2009). Improvements in daylighting performance were noted with change in ceiling geometry compared to a flat ceiling.

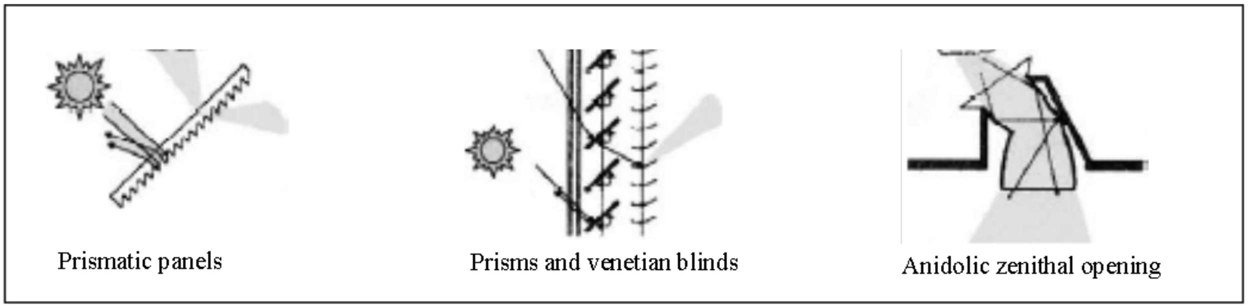
Daylighting strategies for spaces that do not have an equator-facing external wall include **skylights**, **roof monitors** and **clerestory roof windows**. Garcia-Hansen and others have studied these strategies for central-southern Argentina with cold to temperate climates and have found significant energy savings from their use (Garcia-Hansen, Esteves, & Pattini, 2002).

In the following sections a categorized literature review of commercially available daylighting systems including those currently under development waiting for market introduction is provided.

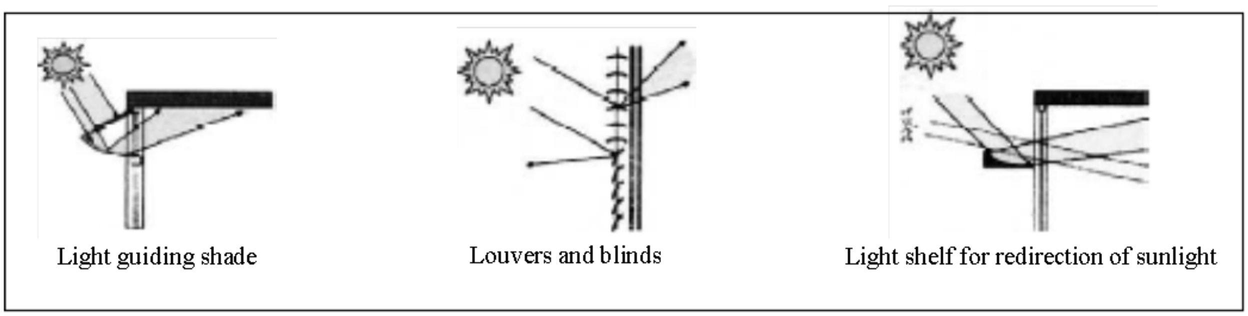
2.1 Categorization of Daylighting Systems

In a modern survey, Martin Kischkoweit-Lopin has classified daylighting systems into two broad categories, (a) daylighting systems that double as shading systems and (b) daylighting systems that do not perform any shading function (Kischkoweit-Lopin, 2002). The first of these two main categories can be further divided into the following sub categories: (i) those using diffused sunlight and (ii) those using direct sunlight The second main category can be divided into four sub-categories (i) direct light guiding systems, (ii) diffused light guiding systems, (iii) light scattering systems and (iv) light transportation systems (Fig. 2).

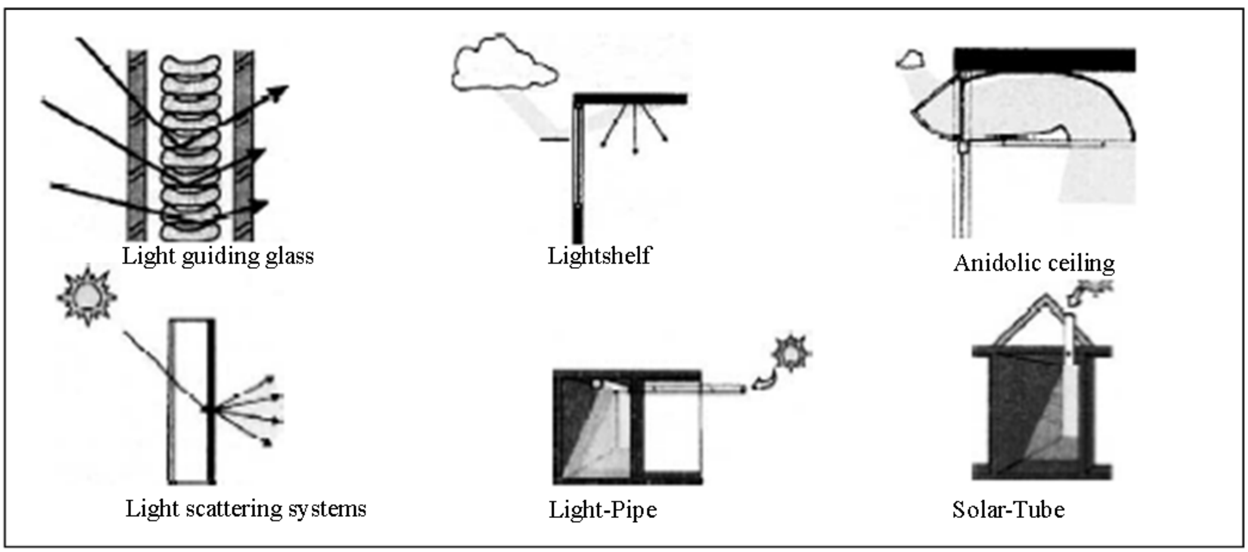
Kischkoweit-Lopin concludes that while the great number of daylighting systems allow for a wide range of application, they must be carefully matched to the building type and its lighting requirements. Otherwise, there could be unforeseen problems such as overheating and glare resulting in a failure of the system. Results of experimental studies carried out at the Building Research Establishment (BRE) on daylighting systems such as prismatic glazing, prismatic film, mirrored louvers, and light shelves have been summarized by Littlefair and others in a widely cited article (P. J. Littlefair, Aizlewood, & Birtles, 1994). The paper concludes that in the case of UK, the use of such devices lower daylighting levels at the back of a room when compared to unshaded windows. Thus, in such a context, these systems should primarily be used as shading devices, controlling glare and allowing more daylight than conventional blinds.



Dayligting Systems *with* shading using *diffused* light.



Dayligting Systems *with* shading using *direct* light.



Dayligting Systems *without* shading.

Fig. 2 Daylighting systems. (Kischkoweit-Lopin, 2002), Used under fair use 2014

2.2 Shading Devices & Systems

2.2.1 Manual Shading devices

Direct solar radiation, with its associated heat, entering interior spaces, may well nullify energy savings from reduced electrical lighting due to daylighting. **Shading devices** are, therefore, often used to block direct sun so that some of the benefits of daylighting still can be utilized. Alzoubi and Al-Zoubi have examined the 'effects of vertical and horizontal shading devices on the quality of daylight in buildings and the associated energy savings' (H. H. Alzoubi & Al-Zoubi, 2010). Their study concludes that optimal orientation of shading devices do provide good illuminance levels without excessive heat gain.

In a study of daylighting classrooms with side lighting in Taiwan Ho and others have found that 'a double-layered sun-shading represents the optimal sun-shading design in terms of achieving a uniform illumination distribution within the classroom (Ho et al., 2008).' Their study found electric lighting cost reduced by 71.5% with the use of daylight as opposed to lighting with artificial lighting alone.

Light scattering properties of a **Venetian Blind** slate used for daylighting application has been studied by Nilsson and Johssen to generate a complete bi-directional scattering distribution function (BSDF) of such a slate in order to predict the daylighting distribution and energy flow through a Venetian blind system (Nilsson & Jonsson, 2010). Tichelen and others have proposed an innovative daylighting system where a special **retro-reflecting solar blind** acts in conjunction with a dedicated reflector at the ceiling in combination with dimmable fluorescent fixtures (Van Tichelen, De Laet, Taeymans, & Adams, 2000). Others have also reported on the energy savings from such blinds for office buildings using dedicated reflector at the ceiling (Van Tichelen et al., 2000). **Micro-Light Guiding Shade** is a special type of static blind system with a compound profile of the slates such that the blinds act as shading by stopping direct beam sunlight while redirecting it further into the rooms to enhance daylighting. Greenup and Edmonds have evaluated the performance evaluation of such a systems using experiments and computer simulations (Greenup & Edmonds, 2004). Olbina has looked at the potential of shading devices to increase daylight in a space. A decision making framework has been proposed to help selection of such devices that can perform as daylighting components as well (Olbina, 2005).

2.2.2 Automated Shading devices

The potential of automated dynamic solar shading in office buildings in reducing energy use has been studied by Nielsen and others through an integrated simulation of energy and daylight, taking into consideration parameters such as energy demand, indoor air quality, daylight availability and visual comfort of the occupants (Nielsen, Svendsen, & Jensen, 2011). This study found dramatic improvement in daylight availability in the interior spaces with the use of dynamic shading as compared to fixed shading. It also showed the importance of integrated simulation studies in the early design phase since separate calculations for parameters such as energy need for heating, cooling and lighting produced conflicting results. The impact of window blinds on daylight-linked dimming and automatic on/off lighting controls was studied by Galasiu and others which showed electric lighting energy savings dropped with the introduction of static blinds while improving with photo controlled blinds (Galasiu, Atif, & MacDonald, 2004).

In a recent paper Park and others points out that daylight responsive dimming systems are not yet widely used because of their poor reliability (Park, Choi, Jeong, & Lee, 2011). This paper describes their research on a new ‘improved closed-loop proportional control algorithm’ which integrates an **automated roller shade** system and a daylight responsive dimming system with significant improvement in performance. Kapsis and others have investigated the daylighting performance of **bottom-up roller shades** with experimental and simulation studies using algorithms they developed to account for various locations and orientations (Kapsis, Tzempelikos, Athienitis, & Zmeureanu, 2010). Their results show potential energy savings for lighting and better performance in terms of Daylight Autonomy with this system, compared to more traditional top-down roller shades. Altan and others in their post occupancy evaluation of a green building at the University of Sheffield, U.K., have found its daylighting strategy, using extensive glazing on the south façade with roller blinds for shading, to be ‘effective in providing a high quality working environment (Altan, Ward, Mohelnikova, & Vajkay, 2009),.’

In order to overcome the shortcomings of manual controls of **venetian blinds** Koo and others have developed a new algorithm that focuses on maximizing the daylighting benefits rather than minimizing the negative impact of daylight (Koo, Yeo, & Kim, 2010). Chaiwiwatworakul and others have studied the potential of lighting energy savings from windows fitted with an **automated blind system** for a tropical climate with improved results in terms of quantity and quality of daylight while achieving energy efficiency (Chaiwiwatworakul, Chirarattananon, & Rakkwamsuk, 2009). One of the early studies on the thermal and daylighting performance of automated venetian blinds was carried out by Lee and others at the Lawrance Berkeley National Laboratory (LBNL) showing significant energy savings with automated Venetian blinds (Lee, DiBartolomeo, & Selkowitz, 1998).

2.3 Light Shelves

2.3.1 Fixed Light shelves

Light shelf performance research can be tracked back to the seventies when, for example, Rosenfeld and Selkowitz have published findings regarding the use of direct beam radiation from the sun for daylighting using reflective louvers (Rosenfeld & Selkowitz, 1977).

In the nineties we find experimental studies carried out at the Building Research Establishment (BRE) on daylighting systems such as prismatic glazing, prismatic film, mirrored louvers, and light shelves, which have been summarized by Littlefair and others in a widely cited article (P. J. Littlefair et al., 1994). The paper concludes that in the case of UK, the use of such devices lower daylighting levels at the back of a room when compared to unshaded windows. Thus, in such a context, these systems should primarily be used as shading devices, controlling glare and allowing more daylight than conventional blinds. In a later survey, Martin Kischkoweit-Lopin has classified daylighting systems into several broad categories as shown in Fig. 2 (Kischkoweit-Lopin, 2002). The survey concludes that while the great number of daylighting systems allow for a wide range of application, they must be carefully matched to the building type and its lighting requirements. Otherwise, there could be unforeseen problems such as overheating and glare resulting in a failure of the system. Results of experimental studies Other experimental research on light shelves as daylighting delivery systems has been conducted by Abdulmohsen to investigate their effectiveness in terms of redirecting direct and diffused solar radiation into the depth of interior spaces while reducing solar heat gain and glare (Abdulmohsen, 1995). Physical scale models were used within a daylighting laboratory to evaluate 15 options for shading and daylighting systems on the south façade of a model office space. In addition, a computer software model was developed to evaluate the energy performance of light shelves. Significant improvements in daylight penetration, glare reduction and energy savings were reported from this study with the use of appropriately designed light shelves.

Light shelf performance was also studied by Claros and Soler for Madrid using 1:10 scale models over a three year period using four types of materials and finishes for the light shelves and several color combinations for the interior surfaces (Claros & Soler, 2002). Performance, defined as ‘relative light shelf efficiency’, was the ‘ratio between illuminance inside the model equipped with the light shelf and a reference model without light shelf.' The mean hourly illuminance variation with the day of the year at a point 0.50m from a south facing side window was the data used for the study. Improved performance with certain light shelves and model combinations was found in the study. Even in cases where the illumination performance was not clearly superior the usefulness of a light shelf as a shading device was noted. The effect of solar elevation on the performance of light shelves was studied by Soler and Oteiza in the context of Madrid using 1:10 scale models (Soler & Oteiza, 1996). Claros and Soler used scale models again to compare the daylighting performance of light shelves and overhangs for a south facing opening in Madrid, Spain (Claros & Soler, 2001). Results show better performance of light shelves than overhangs for the same solar protection. The effect of external light shelves in the context of high-rise commercial developments in Hong Kong has been studied by Close with the aim of transporting daylight deeper into the interiors (Close, 1996).

2.3.1.1 Adjustable and Controllable Light Shelves

In one of the few publications on adjustable light shelves Raphael has reported about research on active control of light shelves (Raphael, 2011). A methodology has been presented, where the geometrical parameters of light shelves are modified in real time to minimize energy consumption in an office space. The control mechanism for this adaptable light shelf has been treated as a global optimization problem with simulation results showing significant energy savings from active control.

In a more recent research, Rao reports on improved energy savings and occupant comfort from a building perimeter daylighting/shading system incorporating movable internal light shelves (Rao, 2011). In his research an advanced façade system was investigated that had a fixed reflective overhang and a movable internal light shelf system in the upper window, while the view window was fitted with bottom-up roller shades. A classroom space in the Chicago, IL region has been used as a test location for this simulation study. Significant improvement in daylight harvesting and lighting energy savings are reported from the use of the proposed setup.

El Sheikh researched intelligent façade design, and has worked with kinetic louvers as a dynamic daylighting strategy (El Sheikh, 2012). His research presents a parametric design methodology, using simulation tools such as Grasshopper, Rhino 3D, and DIVA. This research tries to find the best louver configuration on a building façade under any given weather condition, by using a genetic algorithm, that would try to achieve a set of daylighting performance criteria defined by the user.

No reference to 'manually adjustable' light shelf system has been found in the literature, indicating an opportunity for research in this area.

2.4 Windows and Glazing Systems

Windows and its components such as glazing and blind systems are also considered as a common daylighting apparatus. Polato has reported on the daylight and solar energy characterization of **glazing units** for buildings (Polato, 2000). Johnson and others have also looked at the influence of glazing systems on daylighting using the DOE-2.1B simulation program (Johnson et al., 1984). Parameters including orientation, window area, glazing properties (U-value, shading coefficient, visible transmittance), window management strategy have been looked at for multiple climate to minimize energy use. The use of **prism glass** to direct daylight into interiors through the refraction and reflection of sunlight was a common daylighting strategy before electric lighting became common around 1900. Lorenz has investigated the use of prismatic planes on windows with good results in terms of quantity and quality of daylighting for temperate climates (Lorenz, 2001).

Al-Sallal performed an investigation for **optimizing window sizes** in a passive solar house using rules of thumb and load collection ratio (LCR) methods to achieve passive heating, cooling, daylighting, earth cooling and night ventilation of thermal mass (Al-Sallal, 1998). Zain-Ahmed and others have reported 10% energy savings in tropical Malaysia by simply using appropriate window sizes as a daylighting strategy (Zain-Ahmed, Sopian, Othman, Sayigh, & Surendran, 2002). Al-Sallal has also provided a process of optimizing window sizes for daylighting and other passive strategies for hot arid regions (Al-Sallal, 1998).

Windows fitted with electrochromic (EC) glazing is another area of active research in daylighting. In a recent paper, Baetens and others have given a state-of-the-art review of this area of research by comparing 'technologies of electrochromic, gasochromic, liquid crystal, and electrophoretic or suspended-particle devices for dynamic daylight and solar energy control of buildings (Baetens, Jelle, & Gustavsen, 2010).' Piccolo and others have reported on the performance of EC glazing using an experimental setup with a double glazing unit (DGU) where one pane is ordinary clear float glass (Piccolo, Pennisi, & Simone, 2009). Inoue and others have studied the effect of combining EC glazing with thermotropic glazing where a sandwiched polymer gel changes from clear to cloudy at a threshold temperature, allowing solar transmission in cold winter days (Inoue, Ichinose, & Ichikawa, 2008). Page and others have conducted performance evaluation of EC glazing in combination with anidolic daylighting system (ADS) (Page, Scartezzini, Kaempf, & Morel, 2007). Lee and Selkowitz have reported on the investigation of EC glazing at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley, CA, in relation to their work on the New York Times Building daylighting research (Lee & Selkowitz, 2006). Lee and others have also reported on work at LBNL on the development of control systems for EC window-lighting, using three identical test office rooms (Lee, DiBartolomeo, & Selkowitz, 2006). Rosencrantz and others have reported on the efficiency improvements in daylighting and energy use with the use of low-e coating based on SnO_2, supplemented with anti-reflective (AR) coating, as compared to normal low-e glazing (Rosencrantz, Bülow-Hübe, Karlsson, & Roos, 2005). Inoue reports on the practical application of thermotrophic (TT) glass in office spaces with good results (Inoue, 2003). In an earlier paper, Sweitzer has looked at the potential of light pipes, prismatic panels and electrochromic glazing as emerging daylighting technologies of that time (Sweitzer, 1993).

2.5 Advanced Daylight Harvesting Systems

This section gives an overview of daylighting systems that do not fall directly under a traditional window or facade system. Kim and Kim have given an overview of two such optical systems, light pipe systems and mirror sun lighting systems, with the goal of providing building professionals with advice on their selection and application (J. T. Kim & G. Kim, 2010).

2.5.1 Light Pipes

The core areas of deep-plan buildings are difficult to serve by perimeter daylighting schemes alone. Strategies invented to work around this problem include light pipes, which are linear devices lined with highly reflective inner surfaces collecting sunlight from their exterior end and transporting the same into interior spaces through diffusers on the other end. In order to overcome a general lack of design and evaluation guidelines for such devices, Al-Marwee and Carter have surveyed several such systems in 13 buildings in operation and presented several possible methods of performance prediction for such devices (Al-Marwaee & Carter, 2006). Rosemann and Kaase have written about the successful installation and testing of two light pipes at the Institute of Lighting at the Technical University of Berlin (Rosemann & Kaase, 2005). Results from these test sites show promise in energy savings due to daylight harvesting using these devices. Simulation of the performance of light-pipes has been done by Canziani and others for a test class room using various exterior illumination levels (Canziani, Peron, & Rossi, 2004). From the results of these tests the authors have presented application guidelines for light pipes to help building designers with their implementation. Baroncini and others have looked at the potential of a double light pipe for daylighting application where one pipe transports light to a lower floor while the other pipe carries the light further down to a level below the first one (Baroncini, Boccia, Chella, & Zazzini, 2010).

The Tropics, with its abundant solar radiation, has huge daylighting potential. Chirarattananon and others have presented the development of a light pipe system for the tropics to address this opportunity (Chirarattananon, Chedsiri, & Renshen, 2000).

2.5.2 Anidolic Daylighting Systems

Anidolic Daylighting Systems (ADS) (an: without, eidolon: image) use non-imaging optics, like those used in solar concentrators, to harvest daylight for interior spaces. Molteni and others have shown improved luminous performance with the use of ADS to light underground spaces where windows and skylights are impractical and the sunlight trackers or static concentrators have not performed well in overcast sky conditions (Molteni, Courret, Paule, Michel, & Scartezzini). The cost-benefit relationship of such daylight guidance systems have been studied by Mayhoub and Carter in the context of office buildings where they have linear channels of light reflectors to carry daylighting into the interior core of buildings (Mayhoub & Carter, 2011). This study has not found such systems cost effective compared to artificial lighting systems. However, if intangible benefits of daylighting, such as psychological wellbeing, are considered their use comes out to be more favorable.

Scartezzini and Courret tested the performance of three anidolic systems under different sky conditions with experimental setups (Scartezzini & Courret, 2002). A significant improvement in daylight factors in overcast conditions, compared to a conventional double glazing, was found for some of these systems. Linhart and others have made a parametric study on **Anidolic Integrated Ceilings** (AIC), a special type of ADS, for isolating the main influence factors guiding their performance (Linhart, Wittkopf, & Scartezzini, 2010). Wittkopf and others have looked at the energy savings in electrical lighting through the use of AIC for various daylight climates (Stephen K. Wittkopf, Yuniarti, & Soon, 2006).

Another recent study dealing with ADS in office spaces within the LESO solar experimental building in Lausanne, Switzerland by Linhart and Scartezzini found high satisfaction levels among occupants with this type of lighting environment (Linhart & Scartezzini, 2010). Wittkopf and others have used forward ray tracing to derive luminous intensity distribution curves (LIDC) for photometric characterizations of ADS to allow comparison of collector contours in different ADS setups (S. Wittkopf et al., 2010). Wittkopf has also reported on the performance of various anidolic ceiling systems under different sky conditions (S. K. Wittkopf, 2007). Page and others have also looked at the integration of ADS and electro-chromic glazing for office buildings using computer simulations and experimental setups (Page et al., 2007). Han and Kim have reported on the design and testing of a **fiber optic solar concentrator** (Han & Tai Kim, 2010). In this system, a dish concentrator, an optical fiber cable, and a diffuser at the interior end of the fiber-optic cable are used to transport daylight into sunlight-less spaces. Depending on the clearness of the sky conditions, the system has been found to deliver a significant level of indoor illumination.

Earp and others have written about flexible polymer sheets that can transport light up to 10 meters deep into window-less spaces (Earp, Smith, Franklin, & Swift, 2004). The system uses a stack of luminescent solar concentrator sheets and three different colored fluorescent dyes to produce a concentrated near-white light for transportation into the interior.

2.5.3 Light Redirecting Materials and Finishes

A vast range of new materials and finishes have evolved over the past decades to enhance daylighting in buildings. Smith has given a review of the advances made in this area, often at the nano-scale (Geoffrey B. Smith, 2004). Products in this category include angular selective glazing and energy efficient translucent polymers. Another similar product is a light-pipe where multiple sources of light are mixed to create light of specific color values. This procedure increases the efficacy of daylighting at minimum cost while promising new aesthetics and artistic possibilities. Smith and others have also investigated material properties for advanced light guide systems where both the direct and indirect components of solar radiation are utilized to enhance daylighting potential of systems without increasing the associated heat gains (G. B. Smith et al., 2000).

Manz and others have investigated a daylighting system composed of **transparent insulation materials** (TIM) and **translucent phase change materials** (PCM) using the principal of selective optical transmittance of solar radiation in the Swiss lowland climate with promising results (Manz, Egolf, Suter, & Goetzberger, 1997).

2.6 Daylighting Control Systems

According to Park and others **daylight responsive dimming systems** have not yet achieved wide market applications due to their poor performance (Park et al., 2011). The main problem to overcome is the 'variability of the ratio of photo sensor signals to daylight work plane illuminance, in accordance with sun position, sky condition and fenestration condition'. In this paper the authors have described an improved closed-loop proportional control algorithm that shows significant improvement over current systems.

An optimal daylighting controller is proposed by Seo and others which can be incorporated into energy management and control system (EMCS) of buildings to manage the operation of any lighting fixture in a building (Seo, Ihm, & Krarti, 2011),. Energy savings due to the use of this new controller are claimed to be greater than conventional ones. Validation studies done for this controller have indicated the possibility of typical daylighting control simulation studies to overestimate energy savings due to daylighting control strategies. The use of calculated solar radiation data as opposed to measured solar radiation data has also been found to introduce significant error in estimating lighting energy use due to daylighting controls systems. Lindelof describes a fast daylight model suitable for embedded controllers. Results show such a model capable of keeping illumination levels on a horizontal work plane within acceptable range using simple embedded controllers (Lindelöf, 2009).

A hypothetical daylight private office was investigated by Sweitzer already almost two decades ago for application of innovative daylighting systems including light pipes, prismatic panels, and electrochromic glazing (Sweitzer, 1993). Both manual and automatic control scenarios for window, room and task lighting were tested. At the time of the investigation, due to the high cost of these innovative technologies, their application could not be justified on the basis of energy savings alone while the electrochromic glazing showed the greatest potential in terms of personal control and energy savings. More recently, Yang and Nam have looked at the economics of daylight-linked controlled systems for artificial lighting and found energy consumption reduced by 30% on use of such systems (Yang & Nam, 2010). The payback period, according to their study, decreased with the increase of glazing ratio in a building with a payback period of 8.8 years for using fully glazed walls. Energy savings from daylighting is largely dependent on the function of photo-sensors which initiates the dimming or turning off the electric lights as daylight achieves the lighting need of a space. According to Doulos and others the application of such control systems have been hindered by the difficulty of justifying their cost which, in turn, is linked to proper simulation of the working of these controls (L. Doulos, A. Tsangrassoulis, & F. V. Topalis, 2008). In their study five commercial photo-sensors were tested for their spectral response under various glazing scenario in an office room context showing significant difference in performance and thus in their payback period. In a separate study Doulos and others have looked at the role of dimming electronic ballasts in energy saving potential of daylighting (L. Doulos, A. Tsangrassoulis, & F. Topalis, 2008).

2.7 Climate and Socio-cultural Context

Climatic variations are primarily a result of the change in solar radiation received at different parts around the globe. Daylighting design, therefore, has a close correlation with the climate of a region and must be responsive to this in order to be successful. Furthermore, the issue of climate change will bring about changes in daylighting levels as shown by Tham and Muneer (Tham & Muneer, 2011) in their study among cities in the UK. However, human habitation is more than a collection of quantifiable parameters and goes beyond this to encompass cultural and contextual nuances that also modify the daylighting preferences for a place. The following section touches upon these aspects of climate and context as related to daylighting.

2.7.1 Daylighting and (Micro-) Climate

The tropical regions of the world are typically characterized by high levels of year-round solar availability. Daylighting strategy in such climate often incorporates shading to avoid direct solar radiation entering building interiors, thus, adversely increasing the cooling load. Edmonds and Greenup have discussed daylighting strategies appropriate for the tropics including angle selective glazing, light guiding shades, vertical and horizontal light pipes, switchable glazing and angle selective skylights (Edmonds & Greenup, 2002).

Daylighting of interiors is significantly modified by the external objects, which includes vegetation. Hongbing and others have looked at optimization of tree layout between buildings in the context of Shanghai for good daylighting design (Hongbing, Jun, Yonghong, & Li, 2010). Variation of green spaces between buildings with different layouts of tree plantation for variation of tree species and their heights were studied using computer software such as AutoCAD and Sketchup to predict planting and future growth of vegetation and its impact on daylighting.

The correlation between atmospheric turbidity and daylighting has been studied by Navvab and others already almost three decades ago in San Francisco (Navvab, Karayel, Ne'eman, & Selkowitz, 1984). The effect of urban air pollution on daylight transmittance through glazing has later been studied by Sharples and others in the context of Shefield, UK (Sharples, Stewart, & Tregenza, 2001). The loss in transmittance due to air pollution on vertical windows was found not to exceed 10% while the inclination of the window, use of indoor space and the effect of shading overhang, were found to have more significant impact on daylight design. Compagnon has presented a method to assess the availability of solar radiation on horizontal and vertical surfaces in an urban context (Compagnon, 2004). It is a tool to help urban planners optimize new settlements design in terms of daylighting and other passive and active use of solar energy. Littlefair has also written about ways to ensure daylight availability in new and existing sites (P. Littlefair, 2001).

2.7.2 Daylighting and Socio-Cultural Context

‘Daylight is an essential contextual ingredient that characterizes particular places from its counterpart’ write Al-Maiyah and Elkadi in their paper related to the conservation efforts in the city of Cairo (Al-Maiyah & Elkadi, 2007). Here they note how the use of new finish materials in the rehabilitation efforts in parts of the city has led to a different daylight and reflection levels, modifying the identity and visual character of historic urban fabrics. Their paper documents the use of the simulation software TOWNSCOPE to assess the impact of urban renewal on historic districts and proposes appropriate measures to preserve the daylight quality and thus the character and identity of the old city.

A few years before, Belkehal and others have already documented sunlighting strategies and emerging building typologies in built form and construction details of hot and arid urban spaces in the Islamic World, to help foster a context sensitive architecture (Belakehal, Tabet Aoul, & Bennadji, 2004). Saridar and Elkadi have documented the historical development of façade design in Beirut, Lebanon, with the goal of categorizing them according to their daylighting efficiency (Saridar & Elkadi, 2002). Edmonds and Greenup have reported on appropriate daylighting strategies for buildings in high elevations in the Tropics with its high ambient irradiance and need for extensive shading of window openings (Edmonds & Greenup, 2002). Strategies include light pipes, switchable glazing and angle selective glazing among others.

2.8 Measurables and Light Assessment Methods

2.8.1 Illuminance

By definition *illuminance* is the amount of light falling on a surface as opposed to *luminance* which is the amount of light coming off or transmitted through a surface. Daylighting is the diffused component of the solar radiation coming into a room from the sky vault, exterior surfaces, or internal reflection within a building. Perez-Burgos and others have studied the horizontal and vertical component of daylight illumination for Castilla-Leon' region of Spain using physical measurement taken over a year to arrive at an annual behavior pattern for such values for that region under clear sky conditions (Pérez-Burgos, de Miguel, & Bilbao, 2010).

Lowry and Thomas have proposed a simple spread-sheet based daylight illumination calculator for rooms where one can choose from a variety of sky conditions and glazing material properties to predict the resulting indoor daylight level (Lowry & Thomas, 2010).

2.8.1.1 Exterior Illuminance

Daylighting in buildings is fundamentally dependent on the amount of exterior illumination available around a structure. Littlefair and others have reported examples of **experimental studies** at the Building Research Establishment (BRE) on daylighting systems like the light shelf, prismatic glazing, prismatic film and mirrored louvers to assess the daylighting potential of these daylighting systems (P. J. Littlefair et al., 1994). Manz and others have also used long-term experiments and numerical simulations on a prototype wall, samples of phase change material (PCM) and transparent insulation material (TIM), to investigate the potential of using these smart materials as daylighting systems (Manz et al., 1997). This has been done by utilizing the property of selective optical transmittance of solar radiation of these products.

In many developing nations the data on year-round daylight availability for the local context is not available. With the resurgent interest in daylighting such nations have moved to gather these basic data to assist in their daylighting design. Pattansethanon and others have reported on gathering of such data for the northern region of Thailand, finding the daylight availability there to be much greater than in the capital city of Bangkok (Pattanasethanon, Lertsatitthanakorn, Atthajariyakul, & Soponronnarit, 2007). Joshi and others have prepared similar data for the city of Indore in mid-western India using solar radiation data (Joshi, Sawhney, & Buddhi, 2007). Zain-Ahmed and others have also compiled similar daylight availability data for Shah Alam and Bangi, Malaysia (Zain-Ahmed, Sopian, Zainol Abidin, & Othman, 2002). The potential for good daylighting in the tropics has also been established by a study by Chirarattananon and others (Chirarattananon, Chaiwiwatworakul, & Pattanasethanon, 2002).

Daylighting in dense urban fabric is very much influenced by reflected solar radiation off surrounding buildings and the ground. Li and others have proposed a calculation procedure for determining the daylight illuminance reaching a vertical window surface under clear-sky conditions for such urban contexts (Li, Cheung, Cheung, & Lam, 2010). Computer simulations with the RADIANCE software and measured data under real skies have validated the results from their calculation method. In an earlier publication Li and others have reported the use of a **vertical daylight factor** (VDF) as a criteria to ensure daylight in buildings in heavily obstructed urban contexts (Li, Cheung, Cheung, & Lam, 2009). In another publication Li has also given a review of daylighting illumination determinations and the resulting energy savings associated with daylighting use (Li, 2010). Wa-Gichia has used ADELINE **simulation** software to model an urban context with streets and high-rise buildings opposing each other where the exterior surfaces of adjacent buildings act as passive daylighting source for neighboring building interiors (Wa-Gichia, 1998). The reflected component of daylight in an array of multistoried buildings can be a significant source of daylight in the tropics. Narasimhan and Maitreya have used finite difference method for the evaluation of such reflected components of daylight using parameters such as distance between buildings, reflectivity of surfaces and interior finishes of spaces (Narasimhan & Maitreya, 1969). As shown above, in absence of measured data on exterior illumination levels it is possible to predict the value of such illumination levels using established models. Djamila and others have most recently demonstrated the use of two such models to predict the exterior vertical daylight for tropic places such as Kota Kinabalu city in East Malaysia (Djamila, Ming, & Kumaresan, 2011).

2.8.1.2 Interior Illuminance

Daylighting studies are often done using physical scale models and sky simulators. Anderson and others have used physical models and real test buildings at the U.S. Department of Energy's Non-residential Experimental Passive Buildings Program to assess daylighting performance of commercial buildings in terms of interior illuminance among other criteria (Anderson et al., 1987). Thanachareonkit and others have compared the results of daylighting studies using physical models and real buildings to see how closely they match each other (Thanachareonkit, Scartezzini, & Andersen, 2005). They have reported a general tendency of scale model results to significantly overestimate daylight performance as measured through interior (work plane) illuminance and daylight factor profiles when compared to real buildings. According to their study this error can vary between +60% to +105%. Inaccurate mocking-up of surface reflectance, scale model location and photometric sensor properties were found to be the major cause for such discrepancies. Careful mock-up of the geometrical and photometric features of the test model reduced these discrepancies to +30% - +35% in favor of the scale model.

With the exponential increase in computing power of inexpensive computers and availability of robust simulation programs such as RADIANCE for daylighting assessment, there has been frequent use of simulation techniques to evaluate performance of various daylighting systems. Though computing power was still rather small, Viljoen and others studied the daylight implications of office building renovations in Brussels using both scale-model measurements and RADIANCE computer modeling, showing good correlation between the two (Viljoen, Dubiel, Wilson, & Fontoynont, 1997).

2.8.2 Glare

The impact of daylighting on the visual environment regarding glare is quite complex and not easily assessable through experimental or numerical methods. One of the earlier work on glare prediction algorithms and tools has been done by Nazzal, where he has developed glare prediction procedures to help architects and lighting designers design daylit spaces without introducing discomfort glare (Nazzal, 2001). Osterhaus has made a review of the various attempts made to formulate an assessment and prediction model for discomfort glare (Osterhaus, 2005). In conclusion, he has suggested a need for additional research in this area. He has also presented findings from a study of glare issues encountered in daylit office spaces. His suggestions include important design consideration for such spaces and improved ways of integrating computer workstations in such environments. This issue has been picked up by Wienold and Christoffersen in their research on glare prediction models (Wienold & Christoffersen, 2006). They have compared user assessment of glare conditions in Copenhagen and Freiburg with those of existing glare prediction models to find low predictability of current models. Using CCD camera-based luminance mapping technology they have proposed a new glare prediction model, daylight glare probability (DGP) which, according to their tests, shows a much better correspondence with the actual user perception of glare conditions.

Kumarangurubaran has recently developed a user friendly lighting simulation and image processing tool called ‘hdrscope’, which uses High Dynamic Range (HDR) imaging, using fish-eye optics (180°field of view) for glare assessment (Kumaragurabaran, 2012). As computer screens are incapable of depicting real-life glare scenes, false color rendering is incorporated with HDR photography to visualize glare in this tool. The recently developed glare index DGP, also uses false color rendering to depict glare.

2.8.3 User Experience

The effectiveness of daylighting in enhancing user satisfaction has been studied by several researchers. Serra argues that the benefit of natural light goes beyond energy savings and the **aesthetics of views**, but encourages a ‘more respectful, sensitive attitude in human beings towards the environment in which they live (Serra, 1998).’ Chain and others have looked at the effect of daylight’s color on visual performance and pleasantness (Chain, Dumortier, & Fontoynont, 2001). The variation in the **color of daylight** due to glazing material, shading system, color and reflectivity of interior finishes, climate and time of day has been taken into account in the study, developing a method of predicting the color of daylight and its implications.

A window, as opposed to a lighting fixture, is not just about lighting efficacy (amount of light output per unit of energy used). An opening in a wall provides the building occupants a view to the outside, a sense of **connectedness to the exterior environment**, a perception of the change of sunlight and the seasons. Fontoynont, therefore, makes the case that the window industry should give careful attention to the psychological aspects of window design as it tries to develop products of high efficiency (M. Fontoynont, 2002).

Most recent research by Hua and others has studied **user satisfaction** for a LEED Gold laboratory building in an university setting using post-occupancy evaluation (Hua, Oswald, & Yang, 2011). The study focused on creating a comfortable visual environment for the building users while reducing electric lighting demand. Multiple tools were used for the study including occupant surveys, interviews, illuminance measurements, glare study, user behavior and system settings. The study confirmed high level of user satisfaction with their daylit environment while cutting down on energy use.

2.8.4 Energy

Other than for comfort reasons daylighting strategies have long been of interest in respect of potential energy savings. Fontoynont and others have looked at the energy saving potential of electric lighting due to daylighting from roof monitors on single-story office spaces (Marc Fontoynont, Place, & Bauman, 1984). Results showed significant savings from daylighting then even when the electric lighting system efficiency has been enhanced. Later Lam and Li have used **DOE-2 IE** as a simulation tool to assess energy performance of generic commercial office buildings in Hong Kong (Lam & Li, 1999). Singh and Garg have looked at the daylighting potential of three different climatic conditions in India using different type of window configurations for various façade orientations using daylighting software ADELINE 3.0 (Singh & Garg, 2010). Results of this investigation show energy savings potential of daylighting to be highly dependent on window types.

The shading effect of nearby obstructions on the daylighting potential of a building has more recently been studied by Li and Wong, using the computer simulation tool EnergyPlus and regression techniques (Li & Wong, 2007). A strong correlation was found between the external obstructions and energy savings from daylighting. Hviid and others proposed a new building simulation tool to evaluate the impact of daylighting on building energy consumption (Hviid, Nielsen, & Svendsen, 2008). It is claimed that the tool, because of its simplicity, is useful for daylighting design optimization at the early design phase of a building project. The energy savings from daylighting for office buildings in Hong Kong has been studied by Li and Tsang using 35 commercial buildings (Li & Tsang, 2008). Daylighting performance has been further studied in terms of daylight factor, room depth and glare index. Results from the study indicate electrical energy savings of over 25% with the use of proper daylight-linked lighting control. Ihm and others have proposed a simplified method for estimation of energy savings from daylighting by reducing artificial lighting in the context of both US and international locations. Their method uses dimming and stepped daylighting controls to achieve these ends (Ihm, Nemri, & Krarti, 2009).

Meanwhile, LED lighting is quickly becoming a major artificial illumination method and due to long lamp life, higher energy efficiency and versatility it has shifted balances between energy consumption and lighting levels achieved with daylighting systems versus lighting systems. How daylighting can supplement LED lighting to further reduce energy consumption has been studied by Pandharipande and Caicedo (Pandharipande & Caicedo, 2011). They have looked at the optimum level of dimming of LED lighting, for both occupied and unoccupied interior spaces, when daylight is available.

To further explore the complexity of early design decision-making towards energy efficiency Vartiainen and others investigated the relationship between wall/window ratios and façade integrated photovoltaic (PV) systems (Vartiainen, 2001; Vartiainen, Peippo, & Lund, 2000). As one increases the window area of a façade to improve daylighting there is a corresponding decrease in the wall area remaining with potential for installing PV elements. Their research looked at the optimum ratio of window size (daylighting) and possible PV installation for maximum electricity savings in various solar facades in Southern and Northern Europe.

2.8.5 Health

In a literature review on daylighting Leslie has cited research supporting the benefit of daylight in human health and productivity (Leslie, 2003). The effect of daylighting on the length of hospital stay has later been studied by Alzoubi and others (H. Alzoubi, Al-Rqaibat, & Bataineh, 2010). Pre and post-occupancy survey of patients in King Abdullah University Hospital (KAUH) in Jordan has been used for this work. The results show a high correlation between daylight availability in patient rooms and their length of stay in the hospital. The effect of indoor daylighting levels on patients length of stay in hospitals has also been studied by Choi and others by analyzing the daylighting environment in patients' rooms in Incheon, Korea (Joon-Ho Choi, Liliana O. Beltran, & Kim, 2011). Illuminance, luminance ratio, diversity of illuminance in patient rooms, orientations of these rooms and the positions of the heads of the patients' beds in relation to windows and views were some of the variables considered in this study.

The relationship between daylighting and healthy living environments, in the context of apartment living in Korea, has been studied by Kim and Kim (G. Kim & J. T. Kim, 2010). They have focused on the elimination of balconies in modern apartment building design and the resultant increase in too much light, glare and UV infiltration.

2.9 Daylighting Design

Daylight has both a qualitative and a quantitative aspect. The study of quality of daylight and building occupants' perception of it has mostly been studied by survey, post occupancy evaluation, and similar qualitative research techniques. The study of the quantity of daylight has mostly been studied using numerical methods such as field measurements and computer simulation. The following sections highlight some of the key elements in daylighting design.

2.9.1 Daylighting Performance Indicators

Before one can attempt to design a space for good daylighting it would help to quantify what is considered 'good daylighting'. The task is made complicated by the fact that 'good daylighting' is more than just having the right number of foot-candles or lux. Many attempts over a number of years have been made to come up with reliable daylight performance indicators some of which are mentioned below.

Tsangrassoulis and others have earlier used a daylight coefficient approach for the theoretical analysis of various shading systems and the evaluation of daylight in the interior of a room (Tsangrassoulis, Santamouris, & Asimakopoulos, 1996). The effect of different daylighting schemes has also been investigated by Lam and Li, using two fenestration variables: the solar aperture and the daylighting aperture, though this was mainly done to evaluate the energy performance in typical office buildings in Hong Kong (Lam & Li, 1999).

The **Daylight Factor** (DF) method which gives the interior illumination as a fraction of the exterior illumination has been in use for some time to quantify acceptable levels of indoor daylight conditions. Nabil and Mardaljevic have proposed a new paradigm, called the **Useful Daylight Illumination** (UDI) to assess daylight in buildings (Nabil & Mardaljevic, 2006). UDI is a climate-based algorithm that uses time-varying sky and sun conditions to predict daylight availability at any point on an hourly basis.

Tsangrassoulis and Santamouris have proposed a practical methodology to estimate the efficiency of round skylights using the flux transfer approach (Tsangrassoulis & Santamouris, 2000). In an earlier publication they have proposed an average monthly variable, the **Obstruction Illuminance Multiplier** (OIM), to assess the effect of externally reflected component of daylight coming from perfectly diffused south facing vertical facades across from a window opening (Tsangrassoulis, Santamouris, Geros, Wilson, & Asimakopoulos, 1999). A decade later, Chel and others have proposed a modified model for the estimation of daylight factor associated with skylight in domed ceilings of mud houses in India (Chel, Tiwari, & Singh, 2010). The energy saving potential of skylights for different climatic variations in India is also touched upon in their publication. In an earlier paper Chel and others have proposed a similar model for the estimation of daylight factors from pyramid shaped skylight in vaulted roofs of mud houses in India (Chel, Tiwari, & Chandra, 2009).

Walkenhorst and others have studied the short-term dynamics of daylight availability with computer simulation using RADIANCE and DAYSIM (Walkenhorst, Luther, Reinhart, & Timmer, 2002). They have used a 1-minute average of direct and diffused sunlight as opposed to the usual 1-hour means of irradiance data, in an effort to capture the short-term dynamics of daylighting in the process. The authors have reported better quality of dynamic daylight simulation results with this method.

For cooling dominated buildings the efficiency of a daylighting system is dependent on the amount of daylight they can harvest with the least amount of solar heat gain. This is often expressed by the solar heat gain coefficient (SHGC) of a window. Standard computational procedures available to find the SHGC of glazing are not appropriate for the evaluation of innovative daylighting systems such as heliostats. Tsangrassoulis and others have proposed a new formula for the performance rating of such systems (Tsangrassoulis, Pavlou, Santamouris, Pohl, & Scheiring, 2001).

2.9.2 Daylighting Design Tools

Reinhart and Fitz have reported a survey on the current use of daylight simulation on building design where he found the RADIANCE software to be the tool of choice for over half the participants in the survey (C. Reinhart & Fitz, 2006). Their study found that daylighting for building design was more commonly done using simulation as opposed to experimental setup, the traditional approach in earlier days of daylighting design. Another aspect found in this study concluded that the use of daylighting analysis was found more common at the design development stage as compared to the schematic phase. According to this report, the complexity of tools and lack of proper documentation tended to be the major hurdle towards greater adoption of daylighting simulation for building design.

One of the hurdles for daylight simulation was researched by Smith and otherswho have worked on the material characterization requirements for the accurate yet practical simulation of daylighting in buildings (G. B. Smith, Yan, Hossain, & McCredie, 1998),. They have developed algorithms based on bi-directional transmission and reflection (BDTR) characteristics of materials. According to Zain-Ahmed and others, easy to use daylighting design tools (especially for hot-humid climates) were not commonly available (Zain-Ahmed, Sayigh, Surendran, Othman, & Sopian, 2000), . Their paper fills this gap by presenting such a tool for this type of context. Al-Shareef and others have then developed a computer based model for the analysis of shading systems in tropical regions (Al-Shareef, Oldham, & Carter, 2001). Here, multiple parallel slates are used to block direct sunlight while allowing some amount of daylight to come inside. An example would be the Rowshan shading system used in the Hedjazi architecture of Saudi Arabia. Edmonds and Greenup have discussed simulation of tropical daylighting strategies such as angled selective glazing, light guiding shades, vertical and horizontal light pipes, switchable glazing and angled selective skylights using the RADIANCE program (Edmonds & Greenup, 2002).

Capeluto has suggested a simple design method for architects to use during the early design phase of a project to assess the potential of daylighting in office building design based on the sky solid angle subtended from the center of an opening (Capeluto, 2003). This is to help choose between multiple design alternatives, considering existing site conditions, for optimum daylighting.

A numerical simulation methodology for blind control and electric light dimming in an office building was developed by Athienitis and Tzempelikos (Athienitis & Tzempelikos, 2002). They studied a double glazed window with an integrated highly reflective blind system between its two layers of glass - operated by a custom-built computerized building automation system. Daylight penetration and distribution analysis in a near-circular office building in Penang, Malaysia was carried out by Fadzil and Sia (Fairuz Syed Fadzil & Sia, 2004). They performed on-site measurements to study the need for variation in sun-shading design across the façade of a cylindrical building. The collected data was used to validate computer simulations that led to further development of shading strategies.

Gugliermetti and Bisegna have used the **'Superlite'** simulation program to develop simplified algorithms to assess the effect of daylighting with external fixed shading devices (Gugliermetti & Bisegna, 2006). The authors found great reliability in the simple approach they proposed, noting that greater simplification actually led to lower approximation. Alzoubi and Al-Zoubi used the **Lightscape** software to simulate the effect of exterior shading devices on the daylight performance of a typical small office to optimize the shading solution for best daylighting with minimum heat gain (H. H. Alzoubi & Al-Zoubi, 2010). Their study found the presence of an optimal orientation for shading devices that produced the best internal illumination without excessive solar heat gain.

The EnergyPlus program has been used by Ramos and Ghisi to study daylighting in buildings (Ramos & Ghisi, 2010). Their results show the EnergyPlus program overestimating the values of direct and diffuse illuminance in the interior spaces. Ceiling geometry of interior spaces can have a significant effect on daylight distribution within a space due to its influence on the reflection and diffusion of external and internally reflected components of solar radiation. In order to help building designers arrive at optimal ceiling shapes from a daylighting perspective Rakha and Nassar have proposed a design tool, optimized for daylighting, that generates a mesh ceiling form for any space (Rakha & Nassar, 2011). Radiance, Ecotect, and LUA, a versatile scripting language, was used to develop this design tool, which has been found to be a robust yet precise design aid.

Kocifaj has developed an analytical solution for daylight transmission calculations through light pipes with transparent glazing at its bottom (Kocifaj, 2009). This tool, named ROOF_v3 is claimed by its developer to be very fast and accurate. A technique to predict daylight level in office building has been proposed by Kazanasmaz and others using artificial neural networks (Kazanasmaz, Günaydin, & Binol, 2009). The accuracy of prediction by this system has been claimed to be close to 98%. Wong and others have also developed an artificial neural network model for daylit office buildings in the subtropical climate (Wong, Wan, & Lam, 2010).

More recently, a method for the calculation of indoor daylight illuminance named INLUX has been proposed by De Rosa and others (De Rosa, Ferraro, Igawa, Kaliakatsos, & Marinelli, 2009). This calculation code belongs to the radiocity models and results obtained from it show close correlation with measured results from sky scanners. Fakra and others for example, proposed a new model for indoor daylighting prediction by combining several simplified models currently available(Fakra, Miranville, Boyer, & Guichard, 2011),. Their goal was to increase the reliability and improve accuracy of results, while incorporating these into the CODYRUN software for indoor illuminance prediction.

In an attempt to simplify lighting design simulation while achieving higher application rates during early design Reinhart and Wienold propose a more schematic, simulation based analysis tool, the **Daylighting Dashboard**, to assess the design of daylit spaces, using climate-based daylighting data, occupant behavior and glare analysis (C. F. Reinhart & Wienold, 2011).

2.9.3 Decision Making Frameworks

The architectural design process has traditionally relied on experience and intuition to arrive at an optimum solution for a given set of design constraints in creating new designs. Energy concerns and sustainability issues have generated a need for performance-based design. In order to consider and negotiate between the vast number of parameters and decisions related to such a design process, Clevenger has found the traditional experience or precedent based design process unreliable (Clevenger & Haymaker, 2009). Instead, a matrices based framework for high-performance design has been proposed, which objectively evaluates the various issues involved in high-performance design to arrive at an optimal solution. A much earlier attempt at developing such a matrix based decision making framework is the Building Design Advisor (BDA). It is a software environment developed to help the designer with the integrated use of various analysis and visualization tools in all phases of building design (Papamichael, LaPorta, & Chauvet, 1997)

Daylighting design involves a wide variety of influencing factors. Olbina has developed a Decision Making Framework (DMF) for the selection of shading devices based on their luminance and illuminance potential (Olbina, 2005). In this research a generic DMF for the selection and design of shading devices is presented. This generic DMF is further refined by developing a specific DMF related to the visual performance of blind systems and are evaluated on the basis of illuminance and luminance characteristics. Finally three shading devices, a mini venetian blind system, a patented blind system, and an author-designed system are compared to show the application of the proposed DMF system in an applied context (Fig. 4).

In subsequent research Olbina has compared the daylight autonomy (DA) of the three above mentioned blind systems to show how the developed DMF can be used to design and select various blind systems based on daylighting (Olbina & Beliveau, 2007). This research has been further extended through the development of a transparent shading device as a daylighting system, using daylight autonomy (DA) and useful daylight illuminance (UDI) as performance criteria (Olbina & Beliveau, 2009). In a publication focusing on 3D modeling software related to daylighting research Olbina has written about her successful use of Autodesk VIZ as a research tool to validate the developed DMF (Olbina & Beliveau, 2006).

The use of green roofs is one of the trends we see in today's environment-conscious building design. Grant has proposed a framework to balance the various issues associated with the decision-making process in the design of green roofs (Grant & Jones, 2005). Six important variables impacting the design of green roofs have been identified and their individual and collective influence in the design process has been quantified through a weighted environmental index.

High-performance window systems are another component of importance considered in the design process of energy efficient buildings. In order to arrive at the best choice for the various components of such a window system for any given context Haglund has proposed a decision-making methodology (Haglund, 2010). Simulation tools such as RESFEN and COMFEN developed by LBNL, in conjunction with other papers and web-based tools have been used to formulate this decision-making framework.

In a recent dissertation, a decision-support framework has been developed to help architects, engineers and other decision makers make an informed choice regarding the design and application of radiant cooling systems for environmental control of buildings (Ma'bdeh, 2011).

2.10 Conclusion of Literature Review

The following observations can be made from the above literature review:

- Daylighting strategies have been in use in the built environment for hundreds of years.
- Passive daylighting strategies in the form of building shape, form and components were widespread before artificial lighting and climate control became affordable and thus common.
- Recent challenges, such as energy crisis and climate change, have given renewed impetus for incorporating daylighting strategies into modern buildings.

- A general emphasis on ‘high-tech’ solutions can be perceived in the resurgent interest in daylighting as opposed to passive solution.
- Passive daylighting solutions still seem to be an attractive way (low-hanging fruit) to improve energy efficiency and occupant well-being of our buildings.
- The major variables affecting the design of daylighting systems have been well documented by previous researchers, which can be used as basis towards formulation of guidelines to support the development of other daylight harvesting systems.
- No reference could be found in the literature regarding manually adjustable daylighting systems. As has been discussed in chapter-1, there is great potential in this type of daylighting strategy. This research tries to fill this research gap by proposing a framework to support the development of such a daylighting system.

Chapter 3. Research Approach and Methodology

3.1 Research Approach

Exploring the potential of a *manually adjustable* light shelf to enhance the effectiveness of a traditional *fixed* light shelf is what this research is all about. As light shelves have been in use for centuries it is often assumed that much research and development has been done on the topic over a long period of time. Therefore, this research first, conducts a systematic review of the existing literature on the subject. The knowledge domains identified within this review are then categorized into groups and sub-groups to make it easier to extract the gist of what has been done so far. This is done to avoid duplication of efforts and clarify the contribution this research attempts to make to the general body of knowledge on the subject.

Light is a phenomenon that scales well. This means that results obtained from a small-scale test are fairly indicative of what one would see in a full-blown version of the same set-up. However, for successful scaling of experiments to happen, the material properties at the two scales, such as absorptivity and reflectivity of light, must remain the same. In order to explore the potential of manually adjustable light shelves, a scale model of a typical office space was first tested under the open sky. Selected configurations of a light shelf were applied to the opening of this test-space and the resulting indoor daylight levels measured and recorded using photo-sensors and data-loggers. Data obtained from these tests were post-processed to compare the performance of the various light shelf examples.

Simulation studies were also conducted as part of this research. Results from simulation studies can be used to validate experimental results or vice versa. In simulation it is much easier to precisely control the external and internal variables. Climate-based, dynamic daylighting software was used for this research. This software takes into account the climatic variation in ambient daylight availability at any place, giving more realistic results. The output from the simulation studies was post-processed to generate a single-number performance index to facilitate comparison between the various light shelf configurations.

3.2 Research Objectives

The goal of this research is to construct a framework to support the development of manually adjustable light shelf technologies. This primary goal has been broken into several objectives and related sub-tasks, which are described in the following section in greater detail.

3.2.1 Identify relevant influence parameters for manually adjustable Light Shelves

Extensive literature search was carried out to identify factors and variables that influence the performance of light shelves. Emphasis was placed on identifying parameters which were specifically related to the performance of light shelves that can be manually adjusted. This meant identifying a set of features that can be easily changed by a user or building maintenance personnel using their hands or only simple tools. Such a system also called for adjustable features with distinct calibrations that could clearly be marked on a light shelf for easy manipulation by a non-technical person.

3.2.1.1 Derive a limited list of parameters to construct a proof-of-concept

Using the criteria described above a list of light shelf parameters was formulated. This was not an exhaustive list identifying all possible variables. Rather, a few parameters, such as rotation, height and depth of light shelves, were chosen to illustrate a proof-of-concept on how to evaluate manually adjustable light performance. Various light shelf combinations, derived from this limited list, were evaluated for performance to identify the best possible light shelf for specific orientation, location and user preference.

3.2.1.2 Use Exhaustive Search as the Optimization Strategy

The primary premise of this research is ‘manual adjustability’ of light shelves. This means that there can only be a limited number of adjustment settings on a device for it to be easily adjusted by hand or simple tools. Moreover, the goal of initially developing a proof-of-concept, using only a few variables, generates a relatively small list of light shelf combinations. For a limited list like this it was decided to use the concept of brute-force or exhaustive search as the optimization strategy (Wikipedia, 2014). In this method, all light shelf combinations, rather than only a sub-set of all possibilities, is evaluated, to identify the best amongst them in terms of performance.

3.2.2 Develop a performance evaluation methodology

Comparison of performance metrics amongst the various light shelf combinations is a critical part of this research. Performance of light shelves can be defined in many ways. This research looks at light shelf performance only in terms of interior illumination level. It divides this illumination into three broad categories i.e. ‘under-lit’, ‘well-lit’ and ‘over-lit’ areas. However, for ease of comparison, these three categories are converted into a single-value, termed Daylight Index (DI), using a methodology of conversion. A ‘concern factor’ (CF), chosen by the user to represent their subjective concern for ‘under-lit’ and ‘over-lit’ areas in a space, is used to make this conversion.

3.2.2.1 Assess the interior daylight performance of fixed light shelves

The primary method of light shelf performance assessment in this research is climate-based dynamic simulation technique. This method uses Typical Meteorological Year (TMY) data for a given location to account for ambient daylight variations due to climatic factors. Using ‘DIVA for Rhino,’ a climate-based daylighting software, and ‘Grasshopper,’ a graphical programming tool, a parametric simulation loop was constructed. Three light shelf variables, i.e. rotation, height and depth, were chosen for constructing a proof-of-concept regarding light shelf performance evaluation. Each of these three variables was assessed for four settings, making a total combination of 64-sets (4x4x4). ‘Daylight Availability’ (DA) was used as the performance matrix for this assessment. DA is defined as the ‘percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone’(C. F. Reinhart & Wienold, 2011). The ‘occupied hour’ referred to in this definition was taken to be a 9 am to 5 pm work day, 365 days of the year, for this assessment. The ‘illumination threshold’ in the above definition was taken to be 500 lux for this research. The first stage of the research was to assess the performance improvement of a fixed light shelf over that of ‘no light shelf’. To do this, the best performing light shelf from the 64 light shelf combinations mentioned above was compared to the performance of a ‘no light shelf’ scenario as the base-case. The goal was to see if a light shelf, fixed at an optimal position for the whole year, will improve interior illumination level as compared to ‘no light shelf’.

3.2.2.2 Assessing the interior daylight performance of adjustable light shelves

A procedure, similar to the one used in the previous section to assess the performance of a fixed light shelf on an annual basis, was used to evaluate the performance of a seasonally adjustable light shelf. The difference here is the schedule used to define the ‘occupied hours’. A typical year was first divided into four seasons, making the two solar equinoxes and the two solstices, mid-points of these seasons. Next, the best performing annual fixed light shelf was used for the purpose of a 'base-case'. The performance of this fixed light shelf in each of the four seasons was then taken as the 'base-case' for that season. Next, the performance of the previously mentioned 64 combinations of light shelves was compared to one another for each season to identify the best combination for a particular season. This seasonal best light shelf was finally compared to the base-case for that season to assess the advantage, if any, of seasonally adjustable light shelves.

3.2.2.3 Determine how performance is affected by change of orientation.

A similar procedure, as used to find the optimum fixed and adjustable light shelf, was followed to find the effect of change of orientation on light shelf performance. Initially, Blacksburg, VA (Latitude 37.23 N and Longitude 80.42 W) was used as the location for this study. The 64 light shelf combinations described in an earlier section were used to simulate performance in each of the four cardinal directions. By analyzing these results the best light shelf combination for south, east, north and west orientation was determined for an annual time period. Performance of these four optimized light shelves was next compared with the respective 'no light shelf' scenario for each of the four orientations. The results gave an indication of how light shelf performance varied with change of orientation.

3.2.2.4 Investigate how performance is affected by a change of latitude.

The angle of sunlight hitting the ground in any location is one of the major factors in determining the quality and quantity of daylight received at that point. Thus, to assess the effect of latitude on the performance of light shelves, three cities with significantly different latitudes, Miami, Blacksburg, and Boston were chosen. The performance evaluation method used for Blacksburg, VA, in the last section was next extended to the two remaining locations, Miami, FL, (25.79° N and 80.22° W) and Boston, MA. The results derived from testing all three cities were then compared to determine the effect of change of latitude on light shelf performance.

3.2.2.5 Validate simulation results with experimental studies.

Simulation results are often a product of algorithms, which are less than transparent because of proprietary issues. Therefore, conclusions based on output from such 'black box' simulation engines needs to be validated. One preferred method is to tally these results with those obtained from experimental studies. This research was constrained in its experimental studies by the lack of access to an appropriate artificial sky that provides a constant ambient lighting condition. Therefore, experimental studies proved inappropriate for the purpose of this research. However, it was discovered that results from experiments done under clear sky conditions corroborated the results from simulation studies. Therefore, these experiments were used as validation for the simulation output.

3.2.3 Isolate variables that have the greatest influence on performance.

It is useful to know which variable has the most influence on a light shelf performance. This information will allow a manufacturer or user to prioritize the mechanism they would like to incorporate in an adjustable light shelf setup. The performance of light shelves is closely tied to the incident solar radiation and other climatic factors unique to each location. Therefore, parameters that have the most effect on light shelf performance are not universal but will change according to location and context of the building.

3.2.3.1 Develop graphical diagrams visualizing the impact of variables on daylight performance

A graphical illustration method is proposed in conclusion, which shows in visual terms the relative effect of each of the variables on light shelf performance by seasons for any given location. For the three basic variables, i.e. rotation, height and depth, explored in this research, two of them are kept constant while varying a third over its range of settings to see the effect on performance. This is repeated for all three variables over all four seasons, generating a chart of graphs. By viewing these charts the manufacturer or user of a light shelf can quickly get a sense of the relative effect of each of the light shelf variables on performance, categorized by season, and for that specific location.

The research focuses on the potential of seasonal adjustable light shelves to optimize daylight levels in the interior of buildings, which is calculated on an annual basis for a given location. While issues of cost and energy savings are important and need to be addressed in subsequent stages, this research is primarily focused on the quantity of useful light harvested leaving other aspects of daylighting technology for future research.

3.2.3.2 Formulate a decision making framework to identify optimized light shelf configurations and settings.

For the designer or user of light shelves in the field, a simple tool that suggests possible optimized light shelf configurations, given a set of external variables, could be very useful. A graphical user interface (GUI) is, therefore, proposed as a design-aid, in conclusion of this research. This will act as a 'front-end' to access the database of light shelf performance information generated for any specific location by the process described above. This tool or decision making framework will assist manufacturers and users of light shelf to assess the potential of adjustable LS for any given context in terms of indoor illumination level.

3.3 Research Methodology

In order to achieve the research goals and objectives discussed in the earlier sections a set of research methodologies were adopted. These are discrete techniques that have been used for this research to reach the objectives set forth for this study. The following sections describe these methodologies in greater detail. A diagram showing the relationships between research goals, objectives, and methods is shown in (Fig. 3).

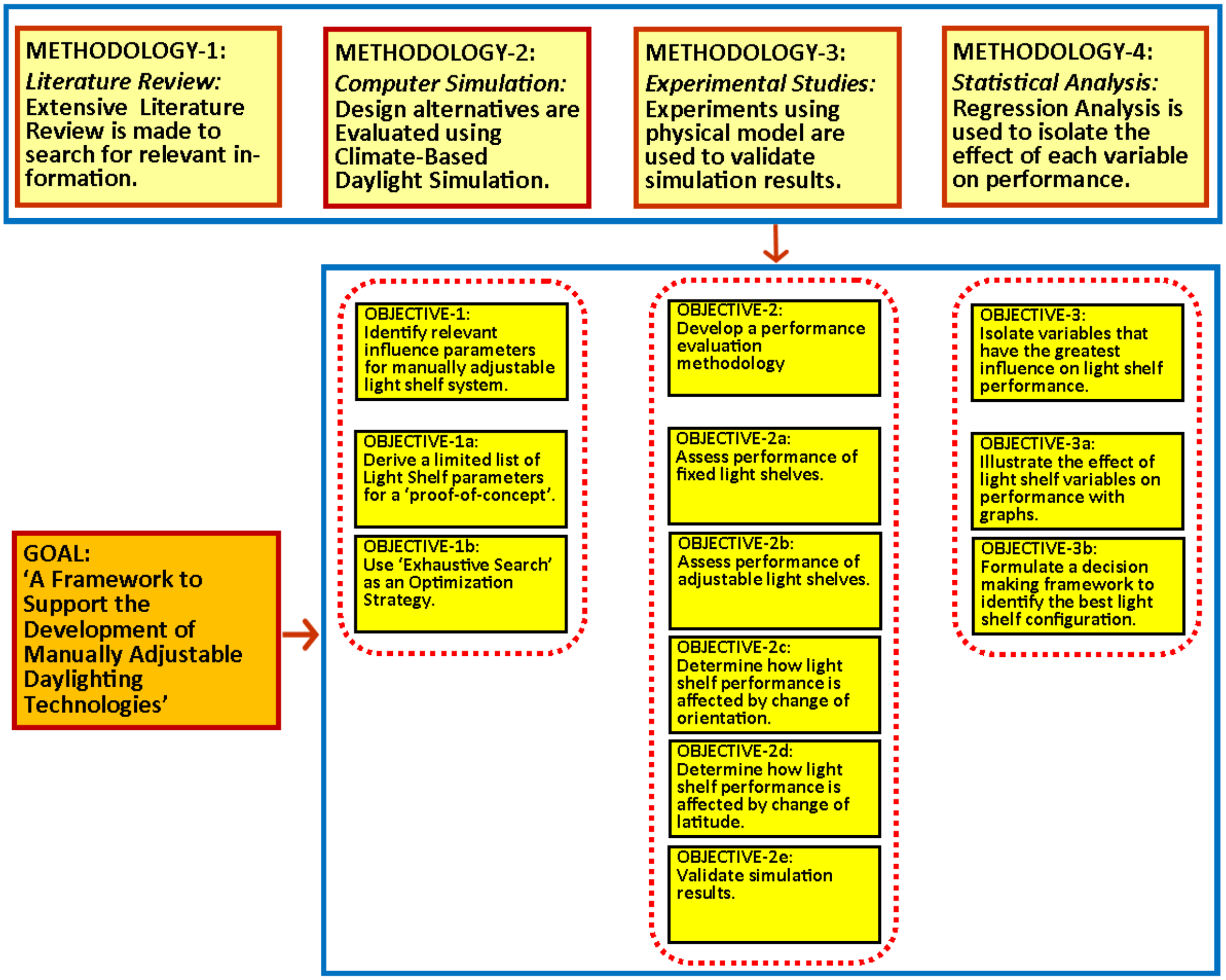


Fig. 3 Overview of Goals, Objectives and Methodologies for this research

3.3.1 Systematic Literature review to identify relevant variables

In order to have a firm grasp on the existing knowledge-base regarding manually adjustable light shelves, a systematic literature review was first initiated. The goal was to identify appropriate context and system variables that are relevant for the design of a manually adjustable light shelf system. This search was also used to narrow down the list of relevant variables to a significant few that could be used to develop a 'proof-of-concept' for this study. Guidelines on optimization principles, to be used for the evaluation of light shelves, were formulated at this stage as well. Performance Index for light shelf assessment was also conceived with the help of this literature search. A decision making framework (DMF) developed by Olbina (Olbina, 2005) provides a comprehensive list of variables and performance parameters influencing daylight performance in interior spaces (Fig. 4). This was used as a starting point in the initial phase of this work. Olbina's work documents the various independent and dependent variables related to the general design of daylighting systems. This framework was used as a basis to derive an appropriate group of variables and performance goals for the present research, focusing particularly on manually adjustable light shelf systems

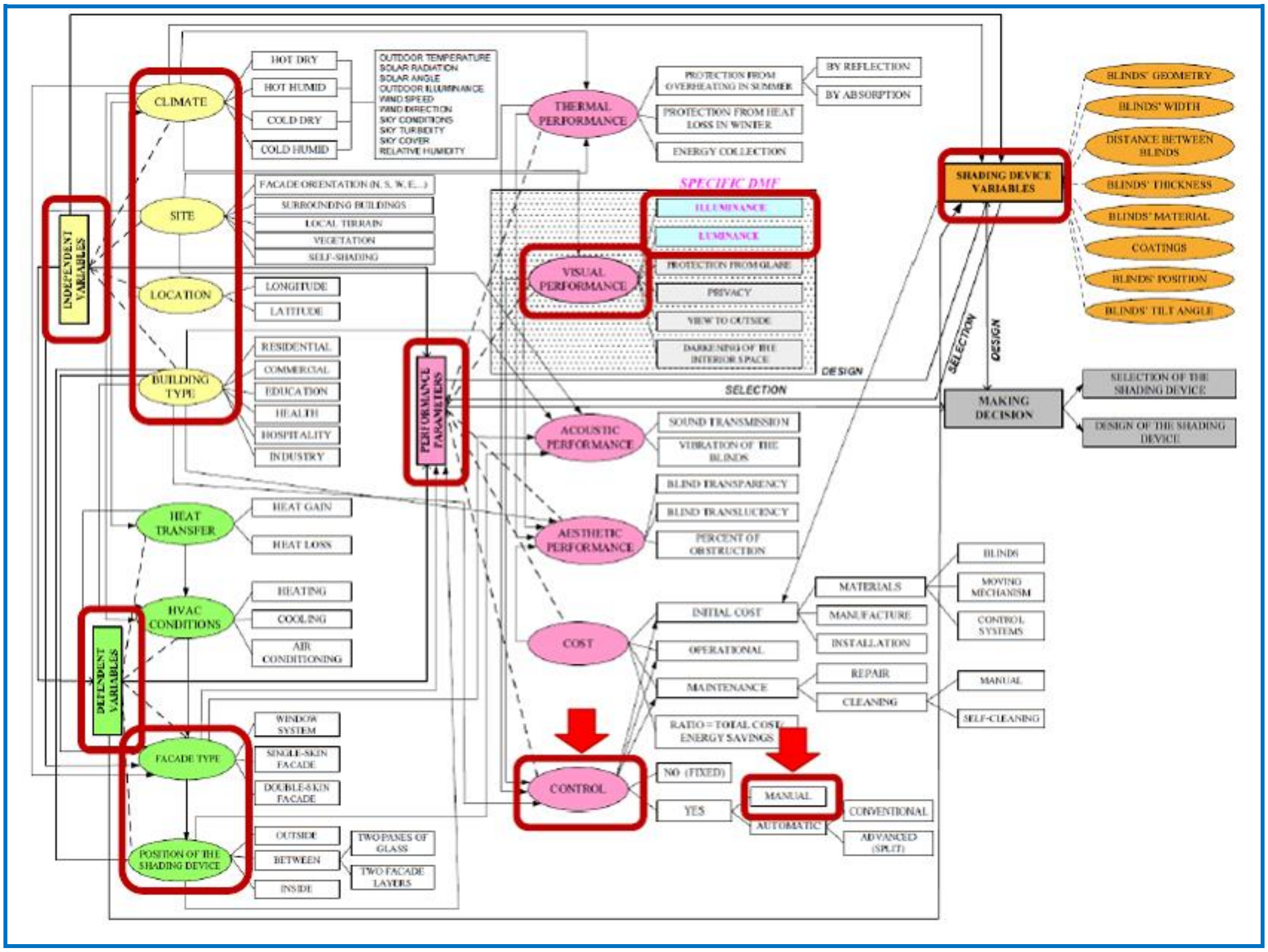


Fig. 4 The General Decision Making Framework by Svetlana Olbina.

3.3.2 Experimental Studies

Compared to simulation studies, experimental studies are often preferred as a research methodology. This is because results from experiments are much more direct and tangible. Simulation results are often generated out of obscure computer algorithms, using assumptions and logic which are hidden from the user.

Experimental methodologies can be well suited for specific comparative daylight research. This is because light scales well. In other words lighting results obtained from a scale-model of a space will be very similar to those obtained from the real space itself, provided the surface properties between the two, such as reflectivity and smoothness, remain the same.

3.3.2.1 Light Source for Daylighting Experiment

Because of the variability of natural light outdoors, daylight experiments are often done indoors, inside artificial skies, which can mimic different sky conditions by changing their lighting setup (Fig. 5). Artificial skies provide a constant source of ambient lighting conditions, making comparison between alternative experiments possible. Only few universities and research institutions throughout the country have this type of experimental facility because they require large space and are quite expensive to build and maintain. However, where available, this type of artificial sky provides an excellent facility to test building models for both diffused and direct sunlight conditions.

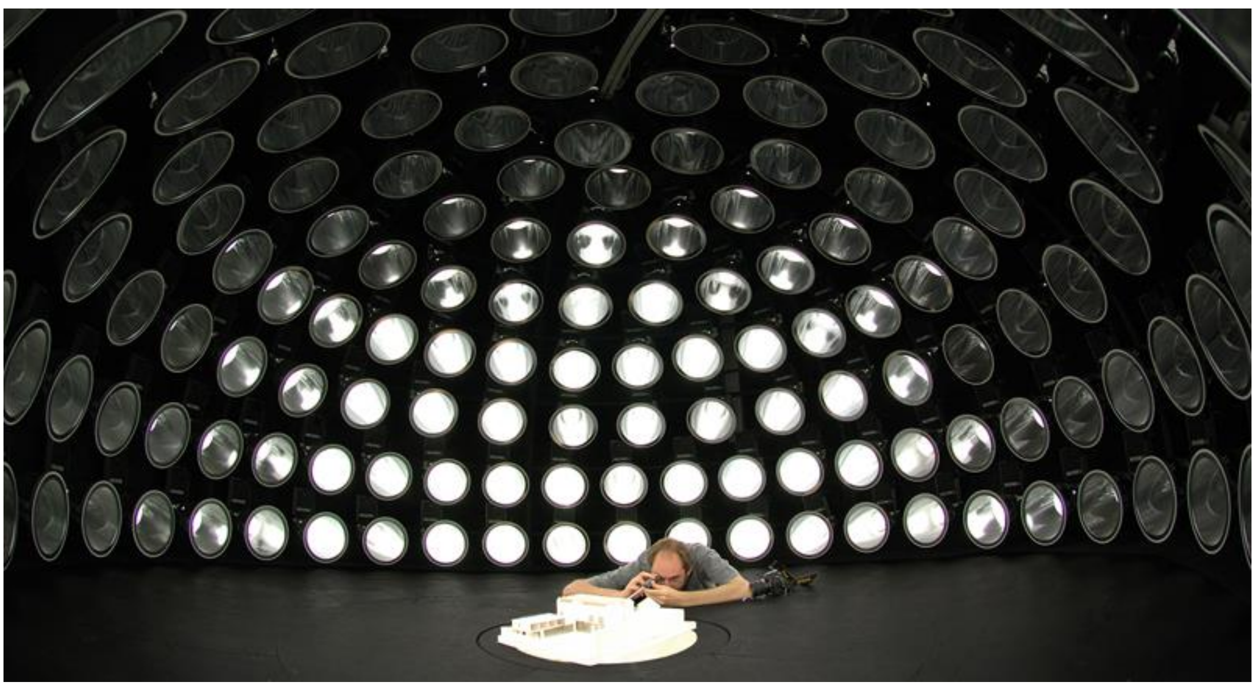


Fig. 5 Artificial sky at UCD, Ireland [Online]. http://erg.ucd.ie/UCDERG/resources.html [Accessed: 17-Apr-2014]. Used under fair use 2014

A much more common type of artificial sky is the 'mirror-box' which uses the principle of inter-reflection to create a lighting environment that matches overcast sky condition quite well (Fig. 6). These types of artificial skies are popular in educational institutions because of their smaller size and affordable construction and operating cost. Mirror-box artificial skies, however, cannot create the condition of direct sunlight and are restrictive in that sense.

Fig. 6 Mirror-box setup at UNCC

The use of natural outdoor light for daylighting studies is still quite common because it is much more intuitive and affordable (Fig. 7). In such experiments the physical model is often placed on 'tilt-tables' that can be rotated on two axes. By using a sundial with such a setup one can easily orient the model to mimic the sunlight falling on it for any given time, day and month of the year.

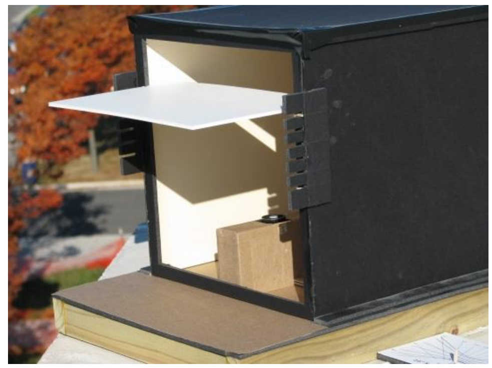


Fig. 7 Daylight study in natural light

3.3.2.2 Daylight Models

Models prepared for daylighting studies are often at a scale of 1:10 or larger. If the models are too big it is difficult to work with them and if they are too small it is difficult to take interior photographs or place light measuring sensors inside them. The color and surface reflectance of daylighting models need to be close to the actual space they represent in order to get comparable measurements. Models need to be carefully constructed to eliminate light leaking through the materials of their construction or their joints. Daylighting models are often constructed in such a way that multiple design options can be tested with a single setup to find the best solutions.

3.3.2.3 Instrumentation and Data Processing

Illumination data is often collected from daylighting models equipped with small, cosine-corrected, light sensors. Cosine-correction of sensors allows them to record the light spectrum in the same range as the vision of the human eye. As a result, the data collected by these sensors from daylighting models corresponds to the perception of daylight people would have if they were to experience that space in reality. Output from such light sensors is typically in the form of electric current expressed in milliamps. The current generated from light sensors is often very weak in strength and thus needs to be amplified and converted into voltage signals that can be recorded with a variety of data loggers. Using various software programs the raw data collected by the data-loggers can then be post-processed for analysis and interpretation.

Fig. 8 Sensors inside daylight model

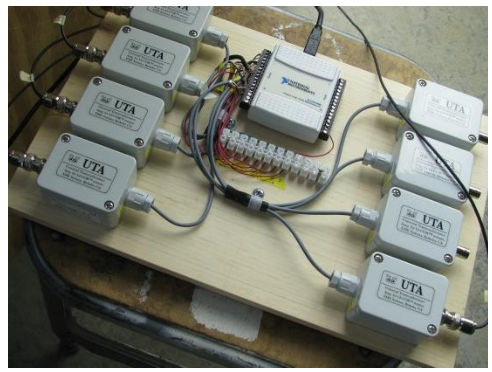


Fig. 9 Data acquisition setup with UTA amplifiers and NI6008 module..

3.3.3 Computer Simulation

Simulation as a daylight assessment tool for the built environment is becoming increasingly common. A renewed interest in environmentally conscious design is leading to a new emphasis on daylighting. Various building certification programs such as LEED (Leadership in Energy & Environmental Design) now provide credits for incorporating daylighting strategies into the building design. This has brought about a need to provide empirical evidence of successful daylight integration in building projects. As a result, software developers have built on improvements in computational power of common computer systems and started to market an increasing number of programs that can perform daylight assessment in reasonable periods of time. A recent trend in this arena is the availability of climate-based daylighting assessment tools where local climatic variations are taken into account.

Computer simulation, using a variety of relevant software, has been selected as the primary tool of investigation in this research. The advantages of simulation as a research methodology when compared to experiments using physical models include:

- They are far less expensive, allowing more variations to be investigated in a shorter span of time;
- Climate-based variations can be investigated using weather data from any place on the earth;
- Constancy of variables that do not change between experiments can be easily maintained;
- Data derived from simulations are often in a format that is easy to manipulate in post-processing.

3.3.3.1 Simulation Software for Daylighting Analysis

The increasing awareness for climate conscious design has brought renewed emphasis on daylighting strategies in buildings. As a result, most of the software programs that are now widely used for building design and performance evaluation have some form of daylighting assessment capability built into them.

In a recent study, Bhavani has given a partial list of daylight simulation tools from the wide variety of applications currently available in the market, as is shown in Fig. 10 (Bhavani, 2011).

Name of software	Light process	Details/Salient features
RADIANCE	Ray tracing	Global illumination using Monte Carlo method
Relux	RADIANCE engine supplemented with radiosity techniques	in built with ReluxCAD, Energy calculation by EN15193 and DIN18599 standards
ADELINE	Radiosity	ADELINE contains SCRIBE-MODELLER as CAD interface, the lighting tools SUPERLITE and RADIANCE
DIAlux	Integrated ray tracing	Emergency lighting according to EN1838, Energy evaluation according to DIN V18599 and EN15899
Lightscape	Radiosity	Made by Autodesk, possible to change viewpoints without recalculating the scene
Inspirer	bi-directional Monte Carlo ray tracing method	Appearance of aerospace objects and automobiles in outdoor spaces under clear or cloudy sky can be simulated
Rayfront	Ray tracing	Makes use of radiance engine and has interfaces for enhancement of geometry and complexity issues
3D studioMAX	ray tracing	Improved rendering and integration with other toolkits for enhancements
Lumen-Micro	Ray tracing	Product library of over 70 manufacturers' luminaire data
Superlite	Radiosity	Quick on numerical feedback on a given design on aperture, reflectance and glazing
Specter	bi-directional Monte Carlo ray tracing method	Accurate simulation results for models involving arbitrary long sequences of specular and diffuse inter-reflections
ESP vision	Ray tracing	Simulated camera and rendering features
Light works	Ray tracing	Progressive rendering gives immediate feedback of the final image with a fast preview of the lighting and materials within the scene
DAYSIM	Ray tracing	Precise sky modeling taking into account the sun position and real sky distribution

Fig. 10 A list of currently available daylight simulation tools (Bhavani, 2011), Used under fair use 2014

Another recent study at the Danish Building Research Institute, Aalborg University (Iversen et al., 2013) evaluated nine daylight simulation software tools that are in the market today. Five room types were assessed with these programs in terms of daylight factor and depth of daylight penetration. The programs investigated in this study were Radiance, Daysim, VELUX, Daylight Visualizer, DiAlux, Ecotect, Ecotect/Radiance, IESve, LightCalc and Relux (radiosity and raytracing). The room types investigated were (1) simple room, (2) deep room, (3) room with obstruction, (4) room with light shelf and (5) room with borrowed light. Ecotect was not used for room 3 and 5 as it was not capable of simulating these. LightCalc was excluded from rooms 4 and 5 and Relux radiosity from room 5 similar technical reasons. The study found that for the rooms and programs used in the investigation there was remarkable agreement in their output. This study, therefore, supports the reliability and validity of results produced by many of the widely used daylighting software in the market today.

However, the software application tested in the above study investigated ‘point in time’ illumination levels. These results do not account for climatic variations such as cloud cover or precipitation for a given location. A recent development in this area has been the introduction of climate-based dynamic daylight simulation programs such as Radiance, Daysim, Lightsolve and VELUX.

Point-in-time daylighting results can give valuable information regarding daylight for one specific instance, e.g. to evaluate glaring issues or specific illumination requirements during design. However, one needs to incorporate the variability of sunlight over days and seasons if one is to calculate annual savings in energy cost due to daylighting. Climate-based daylighting tools have, therefore, been developed in recent years to address this need. These programs use Typical Meteorological Year (TMY) data for a specific location to calculate daylight performance potential for that location. By using the TMY data, climatic variations such as cloud-cover and direct vs diffused sunlight ratio for a particular location is factored in, while calculating the daylighting performance for that location.

A number of daylighting simulation programs have become commercially available in recent years that allow climate-based daylight analysis. Amongst these the DIVA for Rhino is a prominent one and has been used for this research. DIVA uses RADIANCE and Daysim as its simulation engine which have been well validated in the industry (Jakubiec, 2012).

3.3.3.2 Daylighting Performance Metrics

In order to assess daylighting performance of different light shelf configurations in a space, one has to have a yard-stick to compare them against. A number of performance metrics have been proposed and used over the years including:

- Daylight Factor (DF)
- Daylight Autonomy (DA)
- Useful Daylight Illuminance (UDI) and
- Daylight Availability

All but the first one are climate-based daylight performance metrics. These are described further in the sections below.

Daylight Factor (DF)

This is the oldest of the daylight performance metrics. It is expressed as the ratio of horizontal incident daylight outdoors to that found indoors under a fully overcast sky condition. Its major weakness is that it does not account for any other sky conditions. In addition, as it is a ‘point-in-time’ measurement, it cannot account for the annual variations in daylight due to change of sky cover or sun-angle. In order to overcome these limitations several ‘climate-based’ dynamic daylighting metrics have been introduced in recent years.

Daylight Autonomy (DA)

This is the oldest of the climate-based daylight performance metrics. As defined by the IES Lighting Handbook, 10th edition, published by the Illuminating Engineering Society of North America (IESNA), ‘daylight autonomy’ (DA) is “the simplest and most widely applied annual metric” for climate-based daylight performance assessment. It is “a measure of the percentage of the operating period (or number of hours) that a particular daylight level is exceeded throughout the year” (DiLaura, Houser, Mistrick, & Steffy, 2011). Thus, the DA value of a point in space can vary from 0 – 100. This number represents the percentage of occupied hours when that particular point achieves or exceeds the threshold illumination level.

Useful Daylight Illuminance (UDI)

Daylight Autonomy does not give any indication of the percentage of occupied hours a point in space is under-lit or over-lit. Useful Daylight Illuminance (UDI) tries to address this issue by dividing the illumination level of a point into three categories, for most applications these are the ranges from 0-300 lux, 300-2000 lux and above 2000 lux. It considers the middle group (300-2000 lux) to be the ‘useful’ daylight group while the first and the third group represent the ‘under-lit’ and ‘over-lit’ category respectively.

Daylight Availability

Combining the usefulness of DA and UDI, ‘Daylight Availability’ was proposed as a new climate-based performance metric for daylighting in recent years (C. F. Reinhart & Wienold, 2011). Here the ‘over-lit’ point is specifically defined as any point that receives 10-times the threshold illumination value, for 5% or more of the occupied hours. According to IESNA Lighting Measurement (LM) protocol, any point that has a DA value of 50% or more is considered 'daylit' (C. F. Reinhart & Weissman, 2012). According to IESNA Lighting Handbook, 10th edition, the minimum illumination threshold for a typical class-room or office space tends to fall around 500 lux (DiLaura et al., 2011). For this study the following criteria for daylighting performance assessment has been chosen:

- Daylight Performance metric: Daylight Availability
- Minimum Illumination Threshold (IT): 500 lux.

Daylight Performance Bands:

- Partially-lit: <50% of occupied hours achieving minimum illumination threshold.
- Well-lit: 50 – 100% of occupied hours achieving minimum illumination threshold.
- Over-lit: 10-times the minimum illumination threshold (5000 lux) achieved 5% or more of the occupied hours.

(Note: DA values between the well-lit and over-lit numbers are also in the well-lit category.)

The research focuses on the *daylight redirecting potential* of various manually adjustable light shelf systems by comparing the illuminance level (light falling) on the work-plain of a test chamber resulting from the various mechanisms under investigation. These simulations, therefore, assume a constant level of reflectance value for the internal surfaces of a test chamber and a constant transmittance value for the window opening.

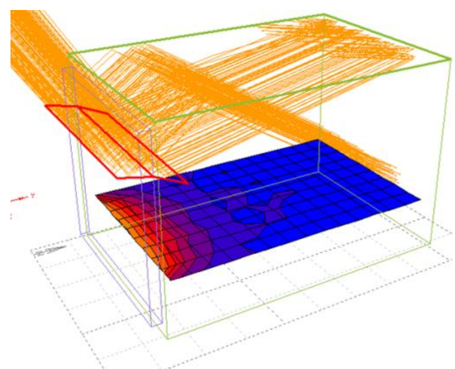


Fig. 11 Light shelves with complex adjustment mechanism.

3.3.4 Validation Method

An initial goal of this research was to make experimental studies under the natural sky the primary method of investigation while using simulation to confirm its results (Fig. 12). A concerted effort over many months was made to achieve this goal. However, due to the difficulty of maintaining a uniform ambient light source between the numerous light shelf studies, this intent could not be materialized and the methodologies had to be

Fig. 12 Experimental study model.

flipped. Thus, simulation studies have been used for the bulk of the investigation in this research. Nevertheless, under clear sky conditions, the results from the experimental studies have been used to corroborate those from the simulation studies as validation for the simulation studies.

Results obtained from simulation work have also been analyzed with statistical methods. Specifically, regression analysis and interaction plots were used to look for trends and patterns in the results of simulation runs.

3.3.5 Development of a Framework

The framework is a 'decision path diagram' that can help a developer to design context and market specific manually adjustable light shelves. Based on the value of the various external variables and user preferences a manufacturer goes through a decision-path to arrive at a set of system variables that are significant to the design of a manually adjustable light shelf for a given context.

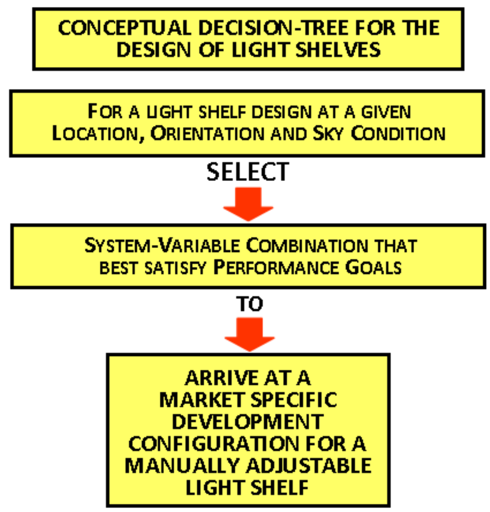


Fig. 13 Diagram of a Framework

Such a decision-path is illustrated in Fig. 14 where only three system variables, i.e. rotation, height and depth of a light shelf, are used to develop a framework for the design of a light shelf. Each variable is tested for three positions, making a total of (3x3x3) 27 combinations. If computer simulations generate one 'illumination matrix' for each of these 27 combinations for a specific location and orientation we will have 27 matrices of daylight performance for a test room. By comparing these sets of values with one another one can arrive at the best combination(s) that satisfy the performance goals set for that space. Thus, the decision-path becomes a means to support the development of manually adjustable light shelf technologies. Once we increase the number of system-variables for a specific location the complexity of the decision-path increases exponentially. For example, the same three basic variables of rotation, height and depth, with four settings each, assessed for four seasons will yield 256 combinations (4x4x4x4). A decision support system can then evaluate these results and recommend answers, considering the use and user preference for that space.

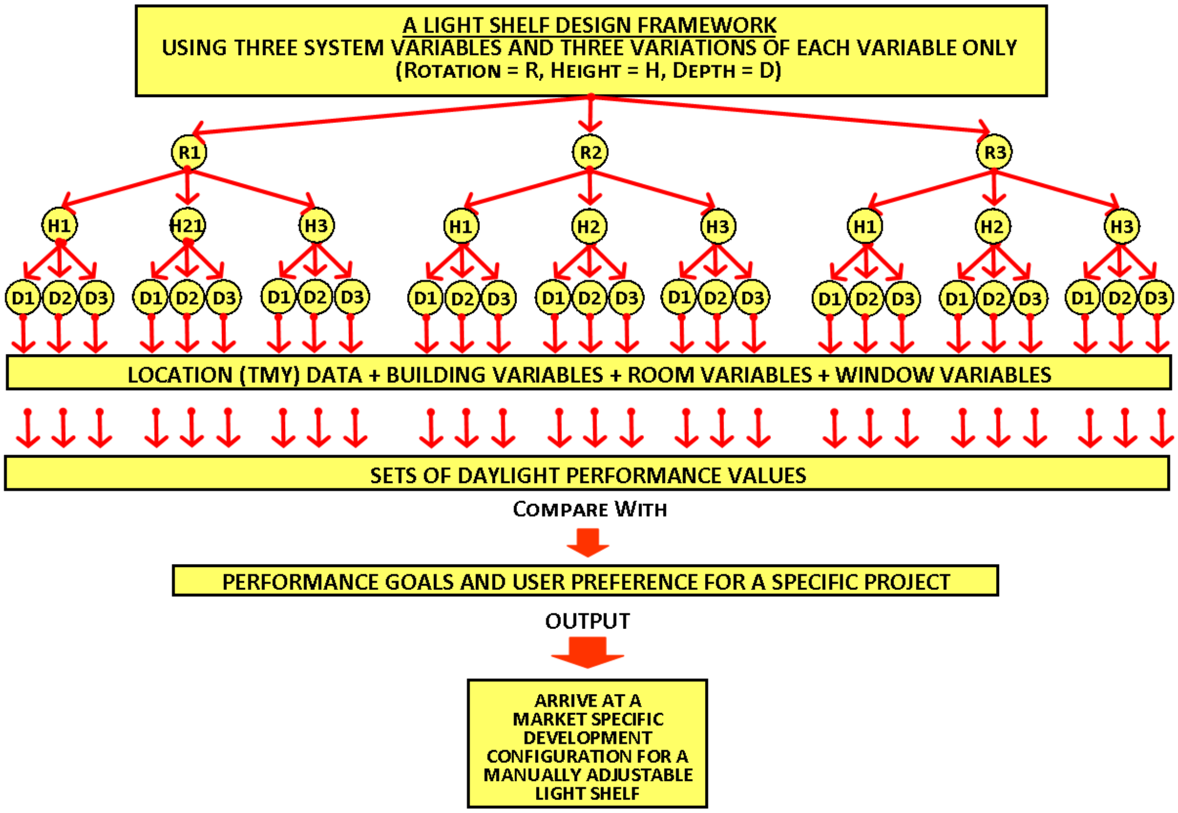


Fig. 14 A Decision Path for an adjustable light shelf configuration selection.

3.4 Research Deliverables

The outcome of this research will be a general framework that will supports the development of manually adjustable light shelf systems (Fig. 15). This framework can help manufacturers develop products focusing on end-users in a specific market. The manual adjustability of these products will call for simple mechanisms that can be manipulated in a limited range and at specific intervals by occupants of a space or by building service personnel to maximize daylight harvesting in the interior. It will also help develop user manuals for manually adjustable light shelf systems providing settings for the maximum benefit in a regional context of such systems.

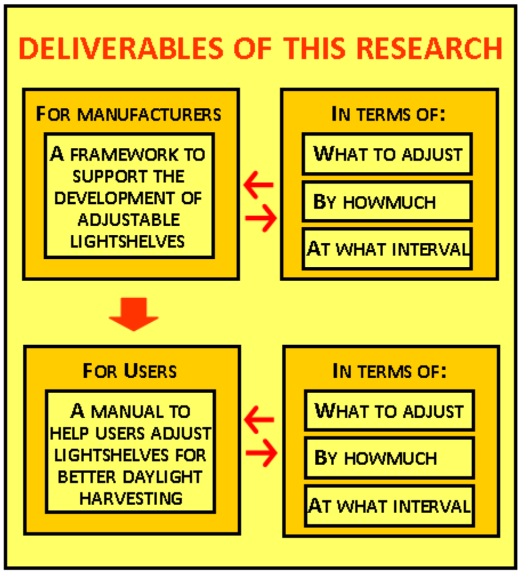


Fig. 15 The outcome of this research.

Chapter 4. Results and Discussions

This chapter documents the core investigations and the results of this research. The systematic literature review has been an integral part of this study. A broad spectrum of publications dealing with daylighting issues was researched and sorted into categories and sub-categories to generate system and performance parameters for the development of manually adjustable light shelve technologies. This was followed by extensive experimental studies to arrive at a sound methodology of performance evaluation of light shelves using natural sunlight as an ambient light source. Finally, simulation studies were carried out using climate-based daylighting software tools to generate data for case variation to be studied for this research.

4.1 Systematic Literature Review

Fixed light shelves as daylight redirecting device have been studied for quite some time and there are many studies that have looked into their design and pointed out performance issues. However, this has been found to be not the case with adjustable light shelves. For example, Olbina's work on a decision making framework for selection and design of shading devices provides a comprehensive list of variables that influence the daylighting levels in interior spaces. It does not, however, touch upon the aspect of manual adjustability of daylight re-directing technologies. The present research, therefore, went further in determining additional variables not covered by Olbina's work that relate to adjustability of light shelves. This was done through a systematic review of the literature on daylighting (Fig. 16). The present state of knowledge in this area has been categorized into sets and sub-sets to identify parameters and variables that are important in the design and operation of manually adjustable light shelves (Fig. 17). The following sections highlight the results of the literature review that informed the present research. It begins with the outcome of the literature review as it relates to this study. Next, it explains the procedures of the experimental studies and their major outcome. Finally, it documents the process of the simulation study and presents the results.

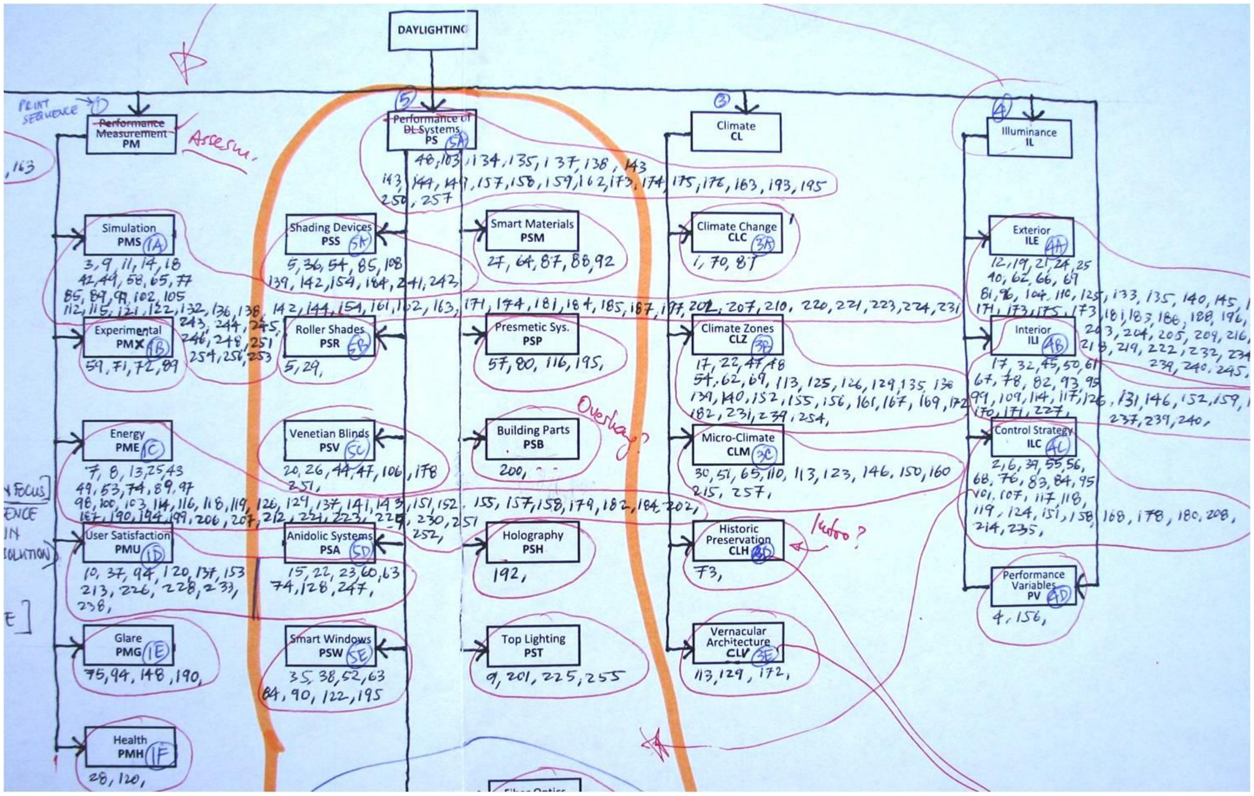


Fig. 16 Systematic review of the literature to arrive at relevant variables.

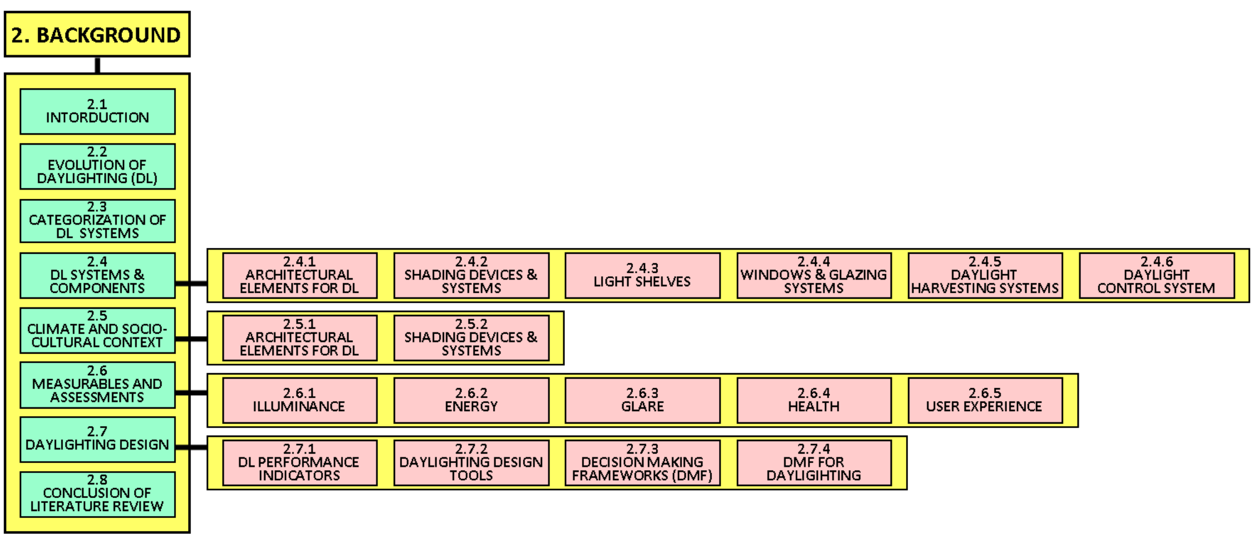


Fig. 17 Categorization of knowledge derived from a systematic literature search.

The systematic literature review revealed many variables that can affect the performance of light shelves. However, only three basic variables, i.e. rotation (R), height (H), and depth (D) were chosen for this study of adjustable light shelves to establish a proof-of-concept (Fig. 18). If each of these three variables had four settings there would be a total of 64 combinations (4x4x4). With the increase in the number of variables or settings of light shelf configurations the total number of simulation becomes increases exponential. For example, if one adds orientation and seasons with four-settings for each to the matrix in Fig. 18, the number of variations quickly increases from 64 to 1024 (64x4x4).

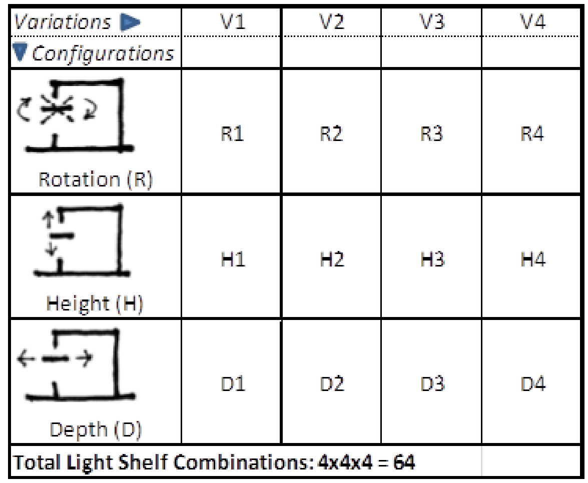


Fig. 18 Light shelf parameters for the initial proof-of-concept.

4.2 Experimental Studies

4.2.1 Introduction

Results obtained from direct measurements of physical phenomena are often preferred in the research community as compared to those from computer simulations. Assumptions and variables affecting an experiment are typically perceived to be more obvious and thus easier to account for. In simulations, the ‘black-box’ of the simulation engine may not be very transparent or accessible to a researcher. Thus, results obtained via simulations are often ‘validated’ using other procedures for verification.

Daylighting experiments with physical models are best done under a sophisticated artificial sky which can mimic varying sky conditions. However, such a facility was not available for this research. Therefore, an effort was made to see if the direct sunlight from the natural sky, calibrated for current ambient conditions, could be used to perform the needed experiments called for by this research.

The primary obstacle of using the sun as a light source is its variability due to cloud cover, time of day and the seasons. It was hoped that by identifying appropriate ‘normalizing factors’ of the results from the experiments one could modify them to allow for comparisons of experiments done under varying sunlight conditions. The goal was to develop an experimental procedure that could produce replicable results.

An extensive effort was made with more than fifty experiment sessions over a period of one-year to achieve the above goal. However, despite all efforts, the experimental investigations have not been successful in controlling and compensating for the many influence factors of daylight experiments to achieve reproducible and scalable results. The following section documents these efforts.

4.2.1.1 Taking off from TAMU research

Abdullah Mohsen's PhD research at the Texas A&M University (TAMU) in College Park, Houston, TX, on light shelf design and its impact on visual performance was the starting point for the experimental approach to this research (Abdulmohsen, 1995). Thus, a 1" = 1'-0" scale model mimicking Mohsen's model was initially constructed (Fig. 19). In the absence of an artificial sky that could simulate direct sunlight at Virginia Tech, the nearest available 'mirror-box' artificial sky at the University of North Carolina at Charlotte (UNCC) was utilized to run some experiments.

Fig. 19 Scale model for research (left) and UNCC mirror-box artificial sky (right).

4.2.2 Experiments at UNCC

4.2.2.1 The Mirror-Box Artificial Sky at UNCC

The closest available artificial sky that had some promise of providing a constant source of ambient light was a 'mirror-box' at UNCC. This type of artificial skies are typically used for daylighting experiments for over-cast conditions since they try to approximate the natural light variation of an overcast sky, having at the zenith three times the illumination level as compared to the horizon. Photographs taken of the UNCC mirror-box with a fish-eye lens and post-processed with the Image-J software demonstrate this phenomenon (Fig. 20).

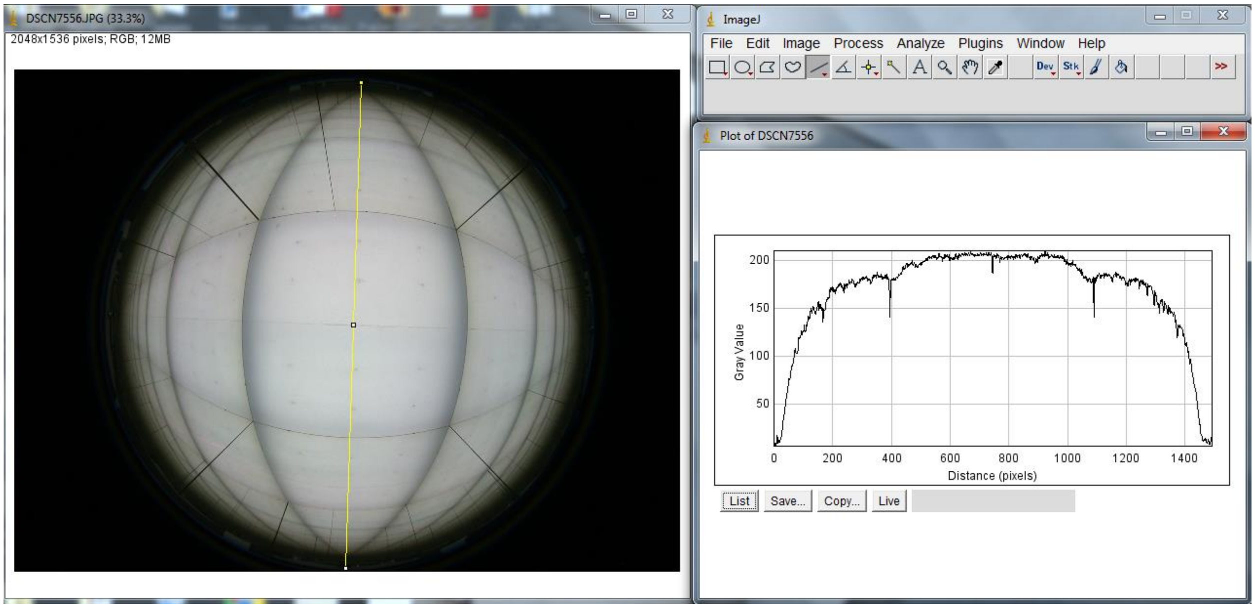


Fig. 20 Fish eye photo of the UNCC mirror box interior and its luminance profile.

4.2.2.2 The UNCC Experiments and Their Analysis

An initial test model at the scale of 1:10 representing a space 10-ft high x 10-ft wide and 15-ft deep was tested to see the viability of the experimental setup (Fig. 21). The ambient lighting condition and that inside the model space was measured with Li-Cor 210 sensors placed outside and inside the model. A National Instrument NI6008 data acquisition processor with eight input channels picked up the voltage signals that were converted by a UTA from the milliamp signals generated by the light sensors and relayed them back to the National Instrument ‘Signal Express’ software for logging (Fig. 22). These data were subsequently post-processed with Excel to find results and trends.

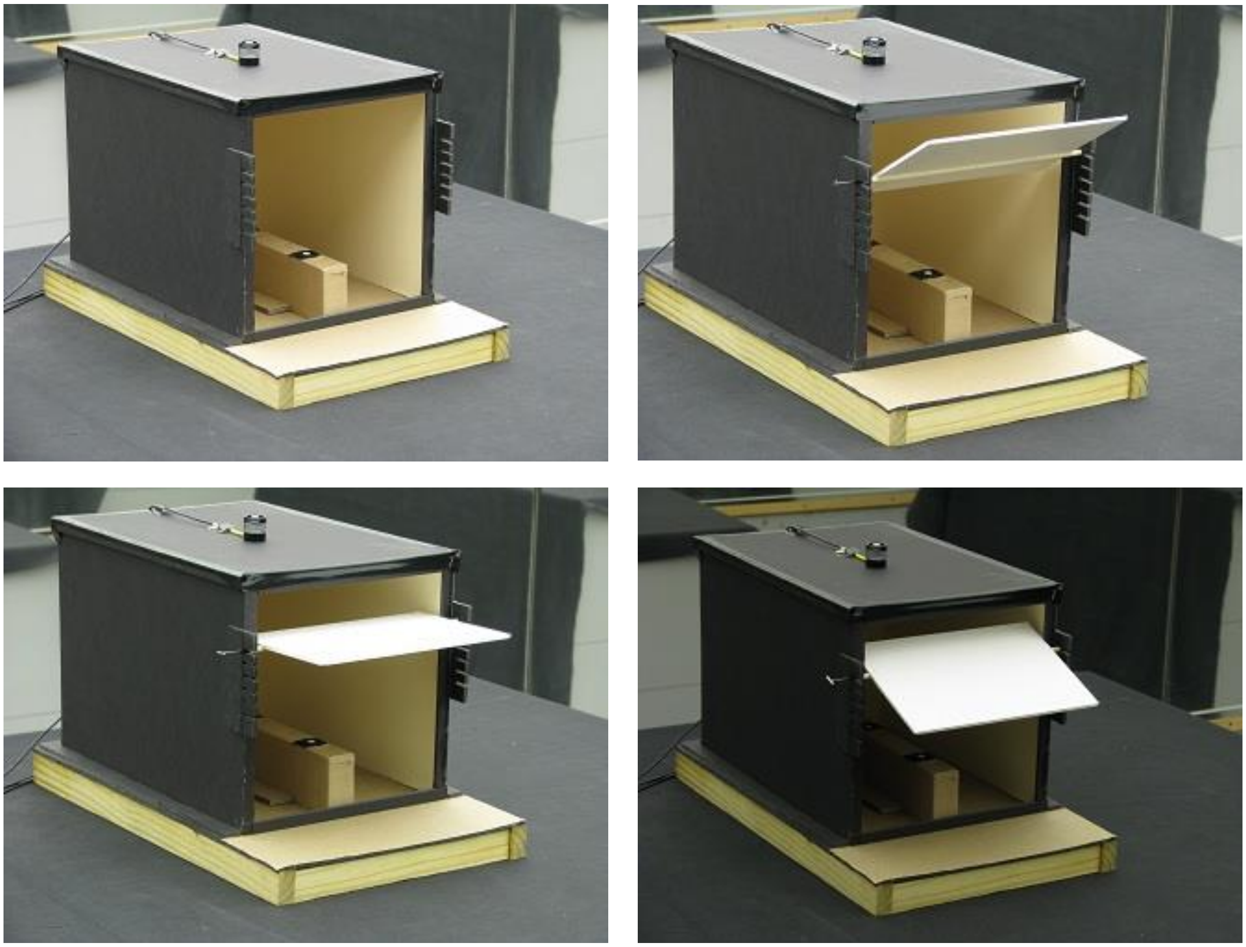


Fig. 21 Initial model to test experimental setup.

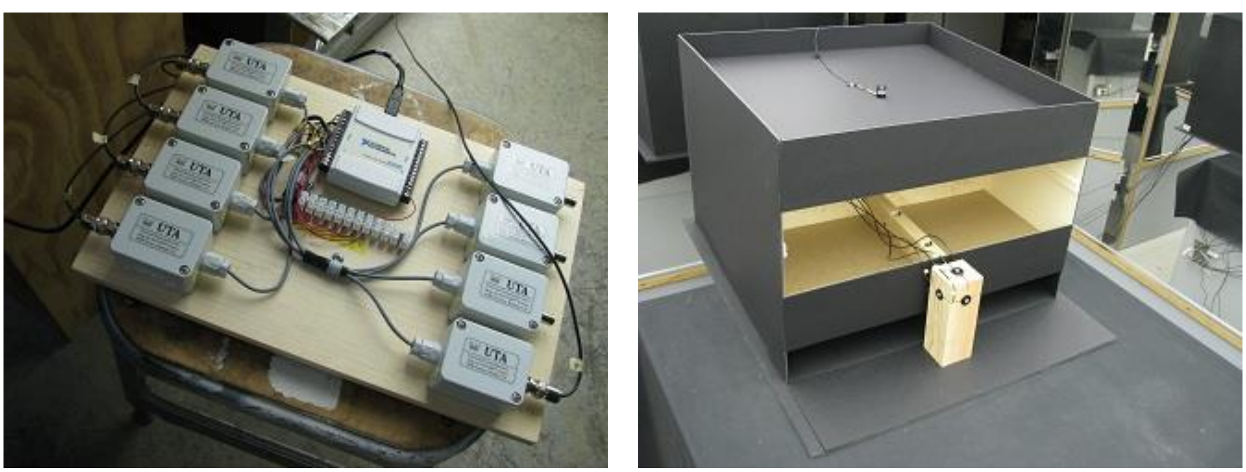


Fig. 22 Sensors and data logger set-up for the mirror-box experiments.

4.2.2.3 Conclusions from the Mirror-Box Experiments

After several experiments using the mirror-box artificial sky at UNCC it was apparent that the lighting variations recorded from within the model spaces due to change of light shelf positions was not significant. It was concluded that the 'overcast sky' condition simulated by the mirror-box must be the primary reason for this. A light shelf would be most effective under direct sunlight and the diffused skylight condition mimicked by the mirror-box was not the ideal condition for evaluating light shelf performance. This conclusion corroborated with Littlefare's findings of light shelf not being very effective under the predominantly overcast sky conditions of United Kingdom (P. J. Littlefair et al., 1994).

4.2.3 Outdoor Experiments at Virginia Tech

4.2.3.1 The VT Model

A space 30-ft deep, 30-ft wide and 10.5-ft high was replicated in a model of ½" = 1'-0" scale, thereby physically measuring 15" wide, 15" deep and 5.25" high inside. The model was made from black foam-core board to minimize stray light penetration. The model was a double-wall construction with a removable interior layer, allowing easy changing of the interior surface reflectance and texture. The double wall construction also helped prevent light leaks. All model pieces were precision cut with a laser cutter. All surfaces of the model were black (0% reflectance, theoretically) accept the ceiling and the light shelf which were made from white foam-core, (80% reflectance). There were laser-cut holes on the side walls of the model to allow precise repositioning of the light shelf for height and tilt (Fig. 23).

Fig. 23 Laser-cut model with precision adjustment and double-wall construction

4.2.3.2 Physical Context

The location of the experiments was an empty, grass covered baseball field surrounded with low height trees and shrubs (Fig. 24).

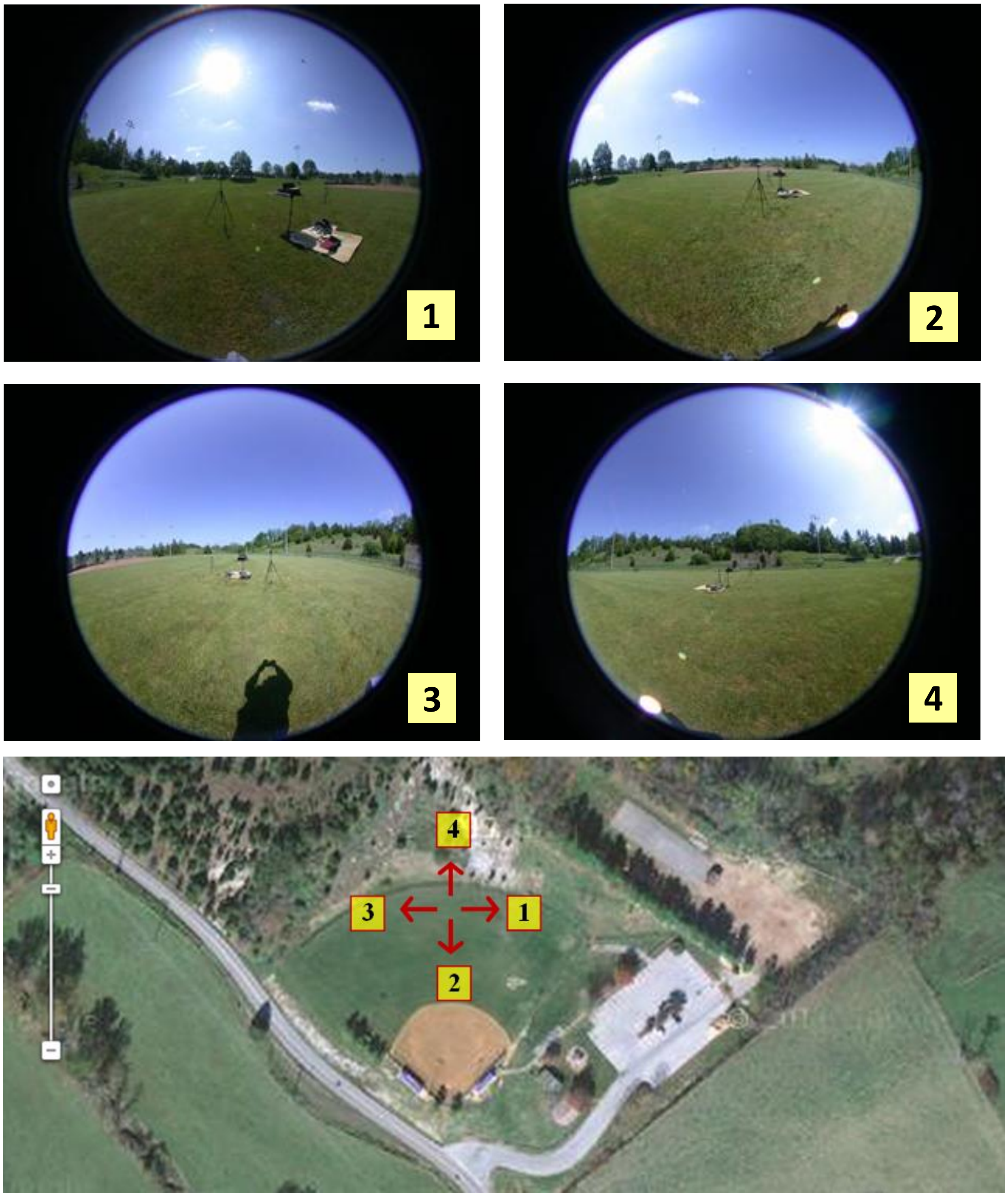


Fig. 24 Ground condition at test-location: 10:50 am, 08 June, 2013 Blacksburg, VA

This was to minimize the effect of ground reflection and reflected light from surrounding structures. The position of the sun was such that the open end of the model, when facing the sun, had its back to the non-grass, sand-covered pitch area of the baseball arena. Thus, light reflected off this lighter ground did not reach the model opening.

4.2.3.3 The Sensors and Their Positions

LiCor Li-210 photometric sensors were used to measure light in the experiments. There were five newer sensors (manufactured November, 2012) S1-S5, one from December 1985 (S6), which was factory recalibrated in April, 2012 and two from 1985 (S0 & S7) that had been recalibrated in-house by comparing them to S1-S5. The first five sensors (S1-S5) were placed at work-plane height of 30” above finished floor, at the center line of the floor space, going progressively from outside to inside. Sensor S6 was on top of the model, measuring ambient light perpendicular to the plane of the model roof. Sensor S0 sat stationary, on top of a tripod, measuring vertical ambient light at all times while S7, located on a back corner of the model roof, acted as a status logger, differentiating between times the light shelf was being adjusted (sensor was covered with cap) and the time intervals when useful data was collected (Fig. 25 and Fig. 26).

Fig. 25 Sun-angle indicator, UTA amplifiers with NI-6008 Data logger and LI-210 sensors.

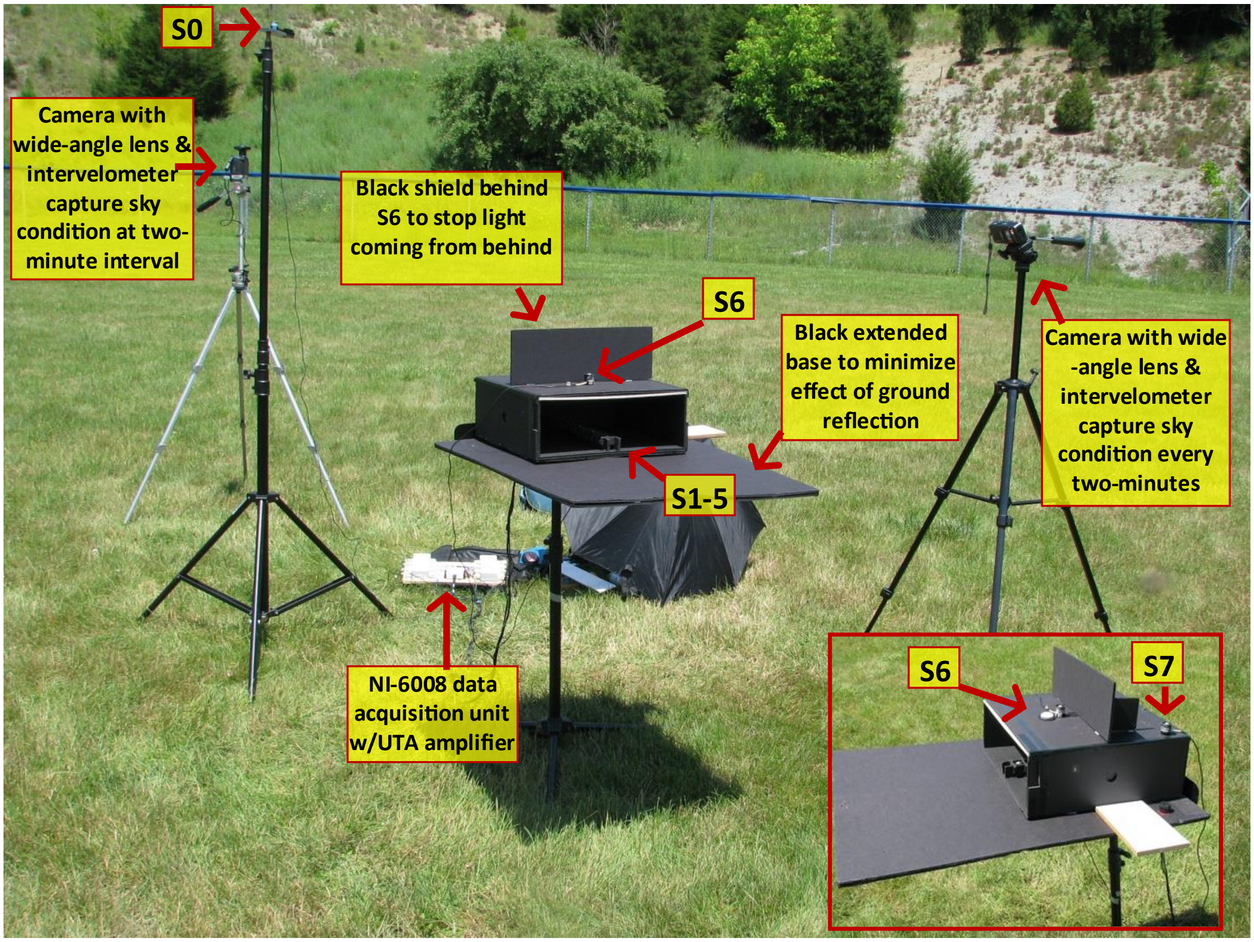


Fig. 26 Experimental setup on a green field to minimize light reflection from surroundings.

4.2.4 Experimental Procedure at VT

4.2.4.1 Recording the Sky Condition

To keep a record of the sky conditions at the precise time of experiments the changing sky was photographed with a Nikon Coolpix 995 camera fitted with a fish-eye lens and connected to a Nikon MC-EU1 intervalometer (Fig. 27). The Coolpix recorded an image of the sky dome once every two minutes (the minimum time interval setting on the MC-EU1). Sky condition records for experiments done on June 22 in Blacksburg, VA are shown in Fig. 28 and Fig. 29 as a representative sample of records from the many sessions carried out around this time. In the beginning of the experiments on June 22, which were carried out between 11:00 am and 1:00 pm, the sky was virtually cloud-less (Fig. 28). However, towards the end of the experiments, some puffs of white cloud floated into the scene of an otherwise blue sky (Fig. 29).

Fig. 27 Fish-eye lens records sky condition and surroundings.

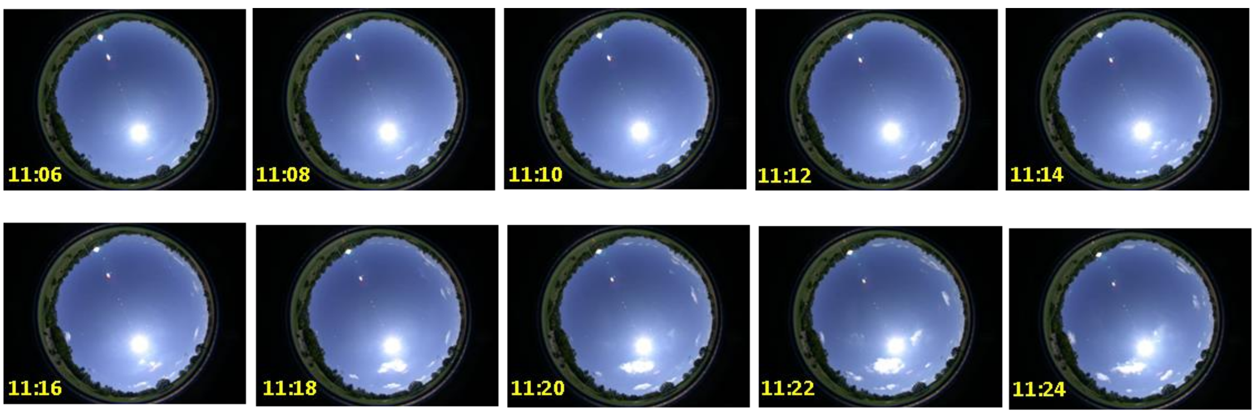


Fig. 28 Sky condition: 11:06 - 11:24 am on 22 June, 2013 at Blacksburg, VA

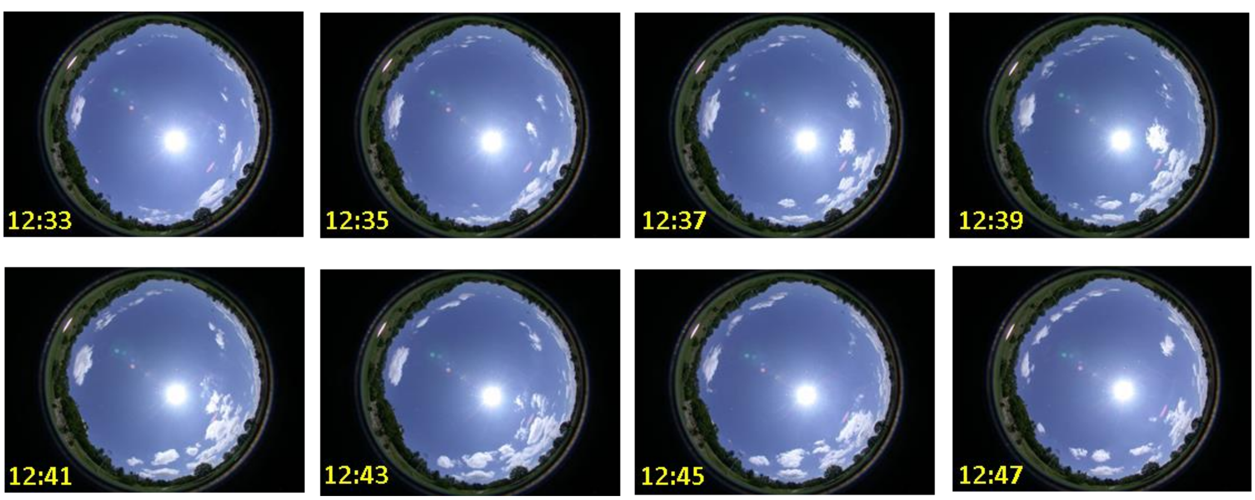


Fig. 29 Sky condition: 12:33 - 12:47 pm, on 22 June, 2013 at Blacksburg, VA

In order to test the performance of light shelves under direct sunlight a set of experiments were carried out at Virginia Tech under the open sky. The goal was to derive an experimental procedure using direct sunlight from the outdoors that could achieve repeatability. Such a procedure would ultimately allow for performance comparisons between a vast numbers of light shelf combinations that this research called for. A number of precautions were taken with these experiments to minimize the effect of ground reflections and variations in the ambient light levels. The test model was placed on a large, black-colored base and the experimental set-up was assembled in a green base-ball field with no surrounding structures to guard against undue ground reflection. All tests had one isolated sensor pointed vertically upwards to record the change in ambient light conditions so that this change could be factored out between experiments in the post-processing stage.

4.2.4.2 Universal Transconductance Amplifier (UTA) Adjustment

The first UTA that was ordered was factory adjusted with a gain factor of 0.2 so that a 4v output would represent 100 klux of illuminance reading. This setting was specified because the factory-recalibrated Li-Cor sensor we initially had (S6) came with an output value of 19.99 microamps for 100 klux of light (multiplier -5.0 klux per microamp). However, when we ordered the new sensors (S1-S5) they came with output value around 34 microamps for 100 klux of light (multiplier of around -3.0 klux per microamp) – almost twice that of the first one. The result was that at higher light levels the new sensors were exceeding the voltage range that could be captured by the NI-6008 data acquisition module. Therefore, we reset the ‘gain factors’ of all the eight UTA’s to 0.1 by changing jumper settings accordingly. However, we found that this adjusted gain factor was not working well for the interior sensors (S3-S5). In the low light levels encountered at the back of the model space, the sensor sensitivity needed to be higher in order to register lower light levels in higher granularity. Therefore, the gain factors of the UTA’s connected with the interior sensors (S1-S5) were adjusted to 2.0, making them 20 times more sensitive than those used for exterior measurements (Fig. 30).

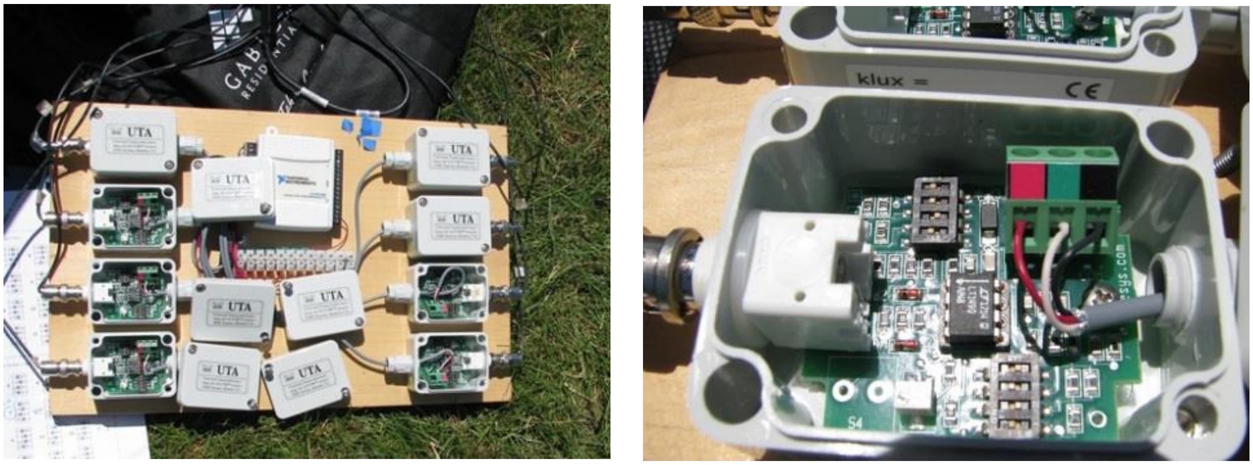


Fig. 30 Gain-factor adjustment of UTA to improve LI-210 sensor sensitivity.

4.2.4.3 Sensor Calibration

Two of the older sensors (S6 and S7) and one of the new (S0) that got accidentally damaged were re-calibrated using the five new factory calibrated sensors. To do this all sensors were placed in a bank and their readings documented (Fig. 32). The first 10 readings from all sensors were averaged (Fig. 31). Multipliers from the five new sensors S1-5 were used to derive five separate multipliers for each of the three unreliable ones (S0, 6&7). The average of these five became the new derived multiplier. For example, the multiplier for S0, as derived from S1 would be M6=C7*M3/B7. The average from all five sensors (S1-5) for S0 is J3= AVARAGE (M6:Q6), giving the new multiplier of 3.11, subsequently used in the volt to lux conversion.

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2			Volts to Lux		klux = v * mult/0.1					New Mult for		Multiplyer for LI-210 Sensors finally used							
3			Conversion		lux = (v * mult/0.1)*1000					S0, S6 &S7		3.11	3.02	2.86	2.90	2.86	3.03	6.46	5.10
4										5.10	S7		5.05	5.11	5.18	5.09	5.05		
5	Avg of first 10 sec data:	New	New	New	New	New	New	Old	Old	6.46	S6		6.40	6.48	6.56	6.44	6.40		
6		Fixed	1	2	3	4	5	1	2	3.11	S0		3.09	3.12	3.16	3.11	3.08		
7		1.74	1.78	1.90	1.90	1.89	1.77	0.84	1.06				AVERAGE						
8		Volts	AVERAGE									Lux							
9	Time	S0	S1	S2	S3	S4	S5	S6	S7		h:m:s	S0	S1	S2	S3	S4	S5	S6	S7
10	sec-1	1.74	1.77	1.90	1.89	1.88	1.77	0.84	1.06		17:56:29	54074	53381	54294	54781	53736	53560	53909	54158
11	sec-2	1.74	1.78	1.90	1.90	1.89	1.77	0.84	1.06		17:56:30	54074	53689	54294	55077	54028	53560	53909	54158
12	sec-3	1.74	1.78	1.90	1.89	1.89	1.77	0.84	1.06		17:56:31	54074	53689	54294	54781	54028	53560	53909	54158
13	sec-4	1.74	1.78	1.90	1.89	1.89	1.77	0.84	1.06		17:56:32	54074	53689	54294	54781	54028	53560	53909	54158
14	sec-5	1.73	1.77	1.90	1.89	1.88	1.76	0.84	1.05		17:56:33	53757	53381	54294	54781	53736	53251	53909	53639
15	sec-6	1.73	1.78	1.89	1.89	1.88	1.77	0.84	1.06		17:56:34	53757	53689	54003	54781	53736	53560	53909	54158
16	sec-7	1.74	1.78	1.90	1.90	1.89	1.77	0.84	1.06		17:56:35	54074	53689	54294	55077	54028	53560	53909	54158
17	sec-8	1.75	1.78	1.90	1.90	1.89	1.78	0.85	1.06		17:56:36	54391	53689	54294	55077	54028	53868	54566	54158
18	sec-9	1.75	1.78	1.90	1.90	1.90	1.78	0.85	1.06		17:56:37	54391	53689	54294	55077	54319	53868	54566	54158
19	sec-10	1.75	1.79	1.91	1.91	1.90	1.78	0.85	1.06		17:56:38	54391	53997	54585	55372	54319	53868	54566	54158
20	sec-11	1.75	1.79	1.91	1.90	1.90	1.78	0.85	1.06		17:56:39	54391	53997	54585	55077	54319	53868	54566	54158

Fig. 31 The factory calibrated S1-S5 are used to derive the multipliers for S0, S6 and S7.

Fig. 32 Finding unknown calibration constants from sensors with known constants.

The bank of new and old sensors was tested for their output under four incident solar angles of 90, 60, 45 and 30 degrees (Fig. 33 and Fig. 34). This was done to see if there was any variation in the output of the sensors due to a change in the solar angle.

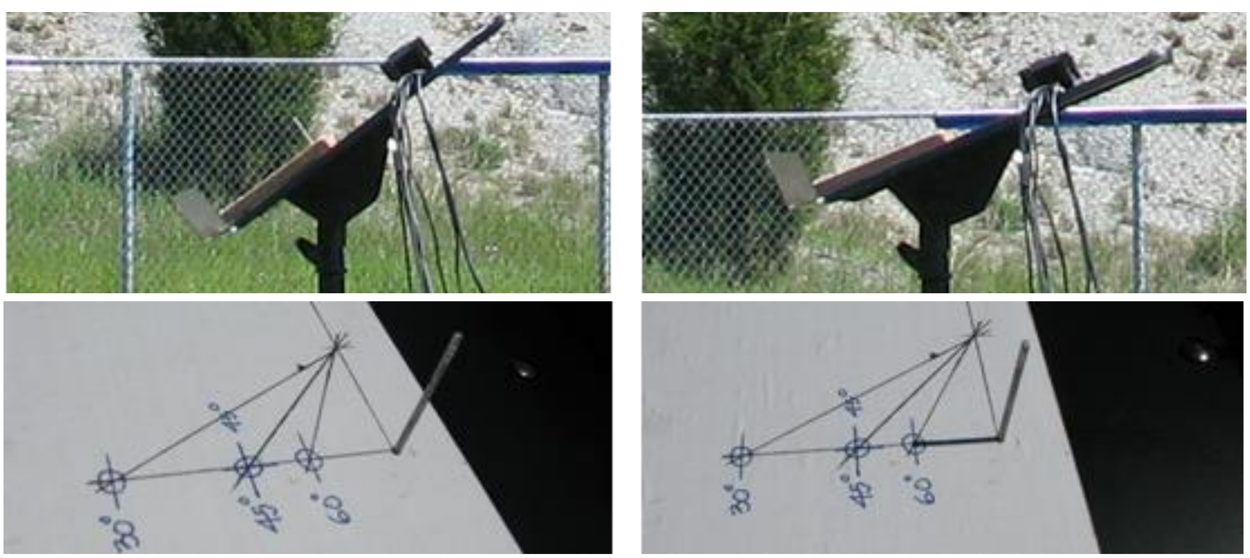


Fig. 33 Sensors tested at 90 and 60 degree sun angles.

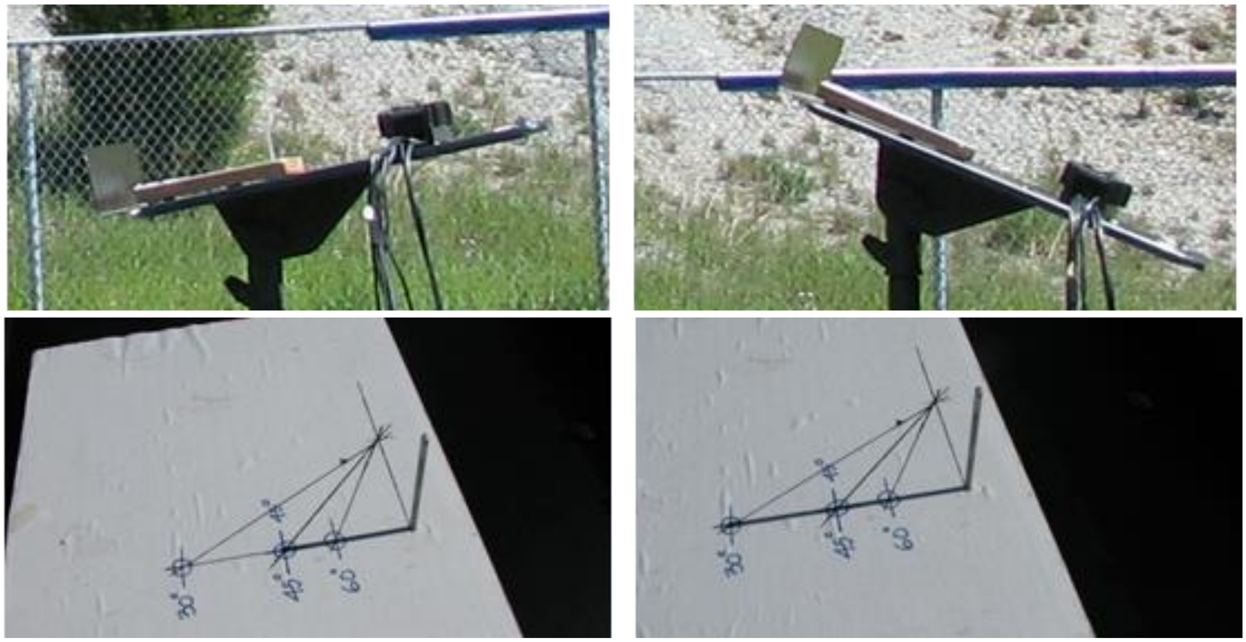


Fig. 34 Sensors tested at 45 and 30 degree sun angles.

4.2.4.4 Repeatability of Experiments with Sensors Outside of Model

In order to have confidence in the results obtained from this experimental set-up one must be able to do the same experiment under different times of a day, different days of a week and different locations and yet be able to arrive at the same results. To see if this was achievable multiple tests were run on the sensors under two conditions, (a) as a bare bank of sensors and (b) as placed inside the model space but without the presence of any light shelf. For the first case one sensor (Fig. 35, S0 on a tripod on the left) was kept constant at a horizontal level while the other seven (S1-S7) were on a bank attached to a tilt-table which was rotated through four solar incident angles: 90, 60, 45 and 30 degrees (Fig. 33 and Fig. 34). Data from S0 was used to normalize variation in incident solar radiation over the course of an experiment.

Fig. 35 Checking for repeatability of results with a bare-bank of sensors.

4.2.4.5 Repeatability of Experiments with Sensors Inside the Model

A central piece of this research was to compare daylighting performance of light shelves as they are taken through parametric variations while attached to a model space. Towards this goal, a bank of sensors (S1-S5) was first tested inside this model space with no light shelf attached, just to see if repeatability of results could be achieved. Analog to the previous scenario (bare bank series), one sensor (S0) was kept stationary on a tripod to constantly measure the vertical component of solar radiation. Additionally, a new sensor (S6) was now introduced, which was attached to the roof of the model and rotated with it to measure the incident solar radiation at the rotated plane. A vertical light shield was placed next to this sensor to ensure that only light coming from the front of the model reached the sensor as it was the case with the sensors inside the model space (Fig. 36). The data from the 90-degree position of S6 was used to normalize the data from the rest of the sensors with the intent to compare results from experiments done on different days and different times of a day.

Fig. 36 Checking for repeatability of results with sensors inside the model space.

4.2.5 Results from VT Experiments

4.2.5.1 Normalizing Variations in Incident Light during Experiments

To be able to compare daylighting performance of light shelf variations one needs to keep the independent variables constant – the most important of which is incident light falling on a light shelf. In our case, while doing daylighting experiments using the ever changing light from the sun and the sky dome, an attempt was made to achieve this by normalizing the data from a sensor (S0) which was kept stationary and horizontal throughout an experiment, recording any variation in the incident light.

The graph in Fig. 37 is a plot of the raw data from an experiment with a bare-bank of sensors where S0 shows the variation in incident light. In the bottom graph of the same figure the value of S0 has been normalized as S0n where S0n is 'S0 normalized to 100,000 lux.' Data from all the sensors in this graph is also multiplied with the same factor used for normalizing S0, thus, showing results as if the incident light has been constant at 100,000 lux throughout the time of the experiment. In this case the methodology of normalization to eliminate the effect of variation in incident light has been successful, as can be seen in the uniformly horizontal lines for all sensor outputs.

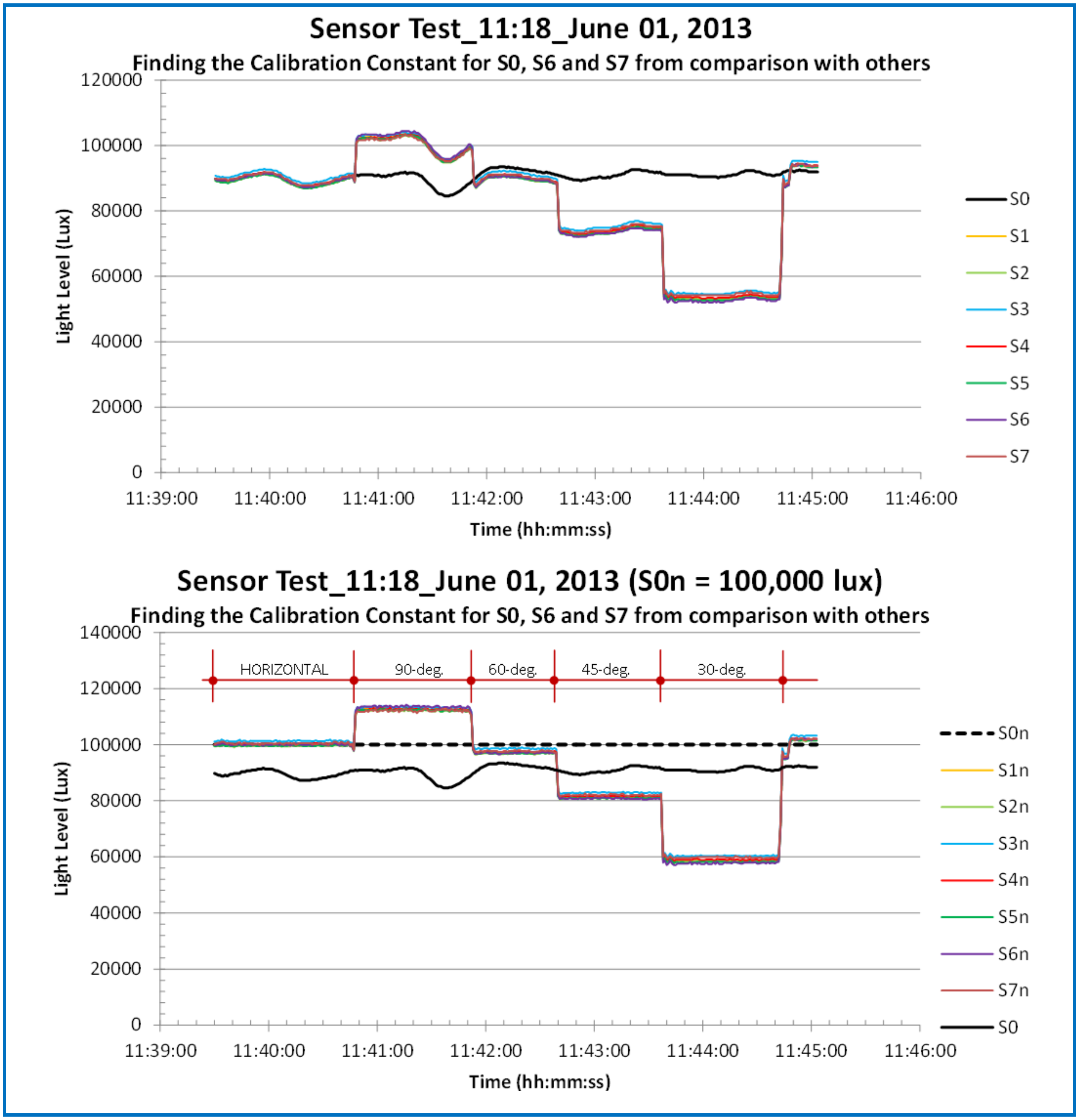


Fig. 37 S0 showing variation in incident light (top); S0 normalized as S0n (bottom)

Note: This is the only experiment reported in this result section (4.2.5) done with a bare-bank of sensors. All other experiments report results from sensors placed inside the model box. No light shelf has been introduced in any of these experiments.

4.2.5.2 Clouds Introduce Significant Errors

Experimental studies found that clouds can introduce significant difference in daylighting results. For example, in Fig. 38, sensor readings on the bottom graph were taken only half-hour later than the ones on the top graph. However, there is a significant difference between the two because of the cloud cover. A normalized version of the bottom graph is given in Fig. 39.

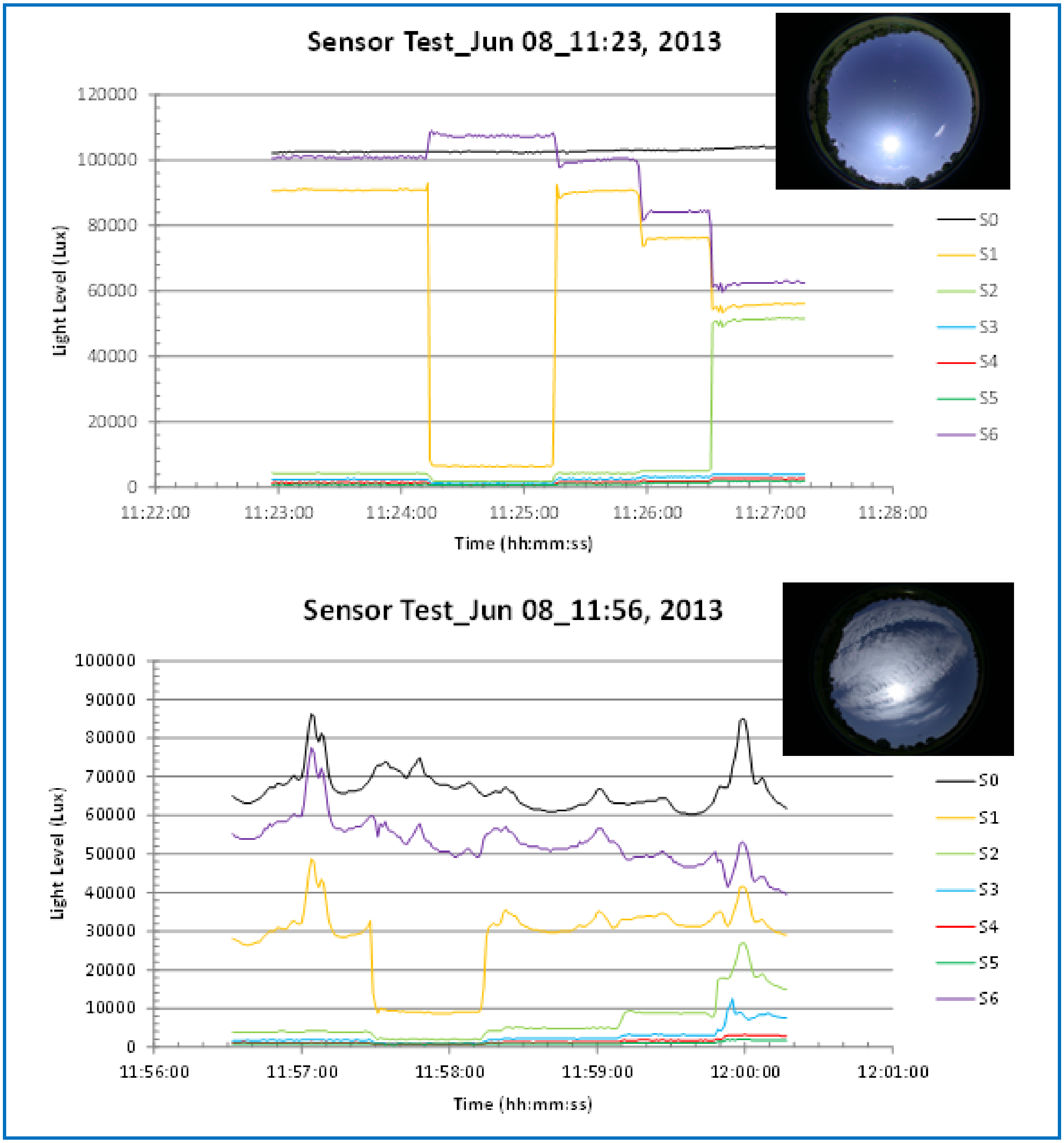


Fig. 38 Cloud cover introduces significant difference.

As can be seen in this graph, the normalization of the data from Fig. 38, bottom did not propagate to other sensor data and make them linear.

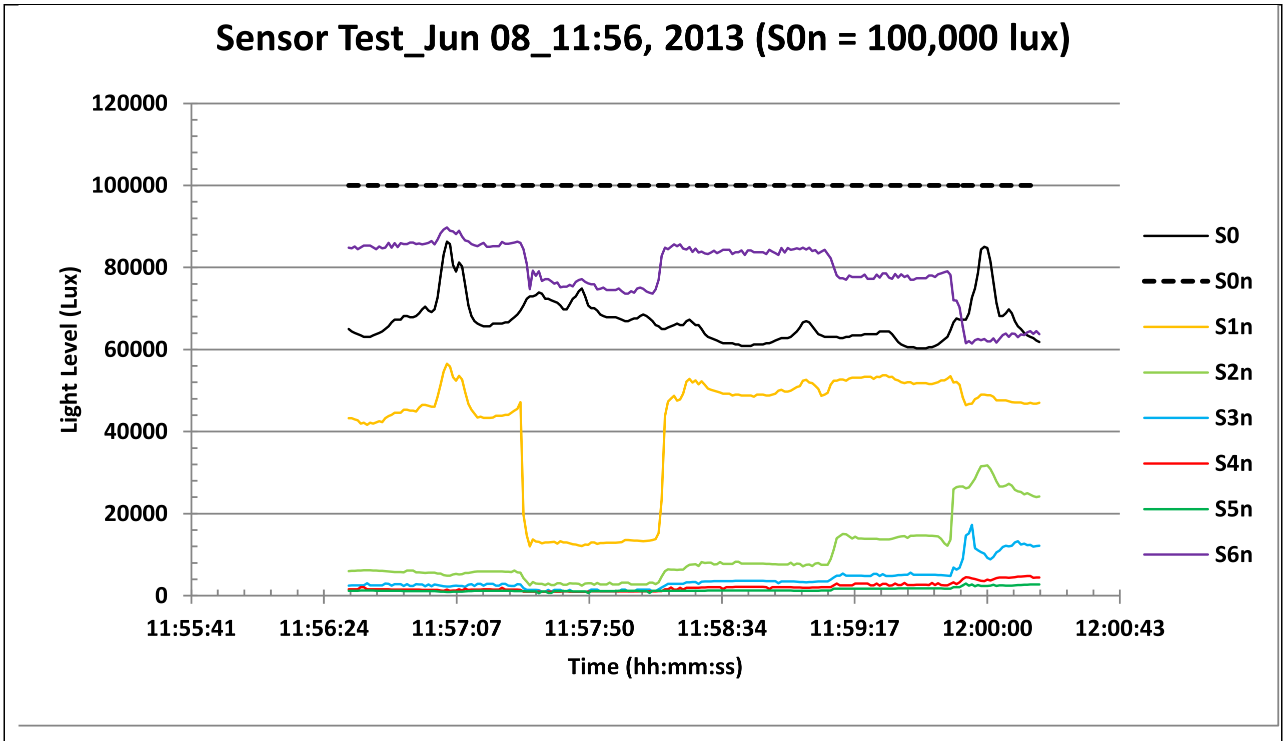


Fig. 39 Normalized data of the cloud cover graph from Fig. 38, bottom.

4.2.5.3 Repeatability of Results between Experiments

An attempt was made to mitigate the result of variations in the incident light *between* experiments by normalizing the 90-deg. part of S6 data from an experiment with the sensors inside the model space. An example of such normalization can be seen in (Fig. 40). The hope was that if the 90-deg. segment of the S6 data (the sensor at the roof of the model space) from a number of experiments was always normalized to common base line (100,000 lux in this case) the variation of incident light falling on different experiments on different days could be brought down to a common denominator, allowing direct comparison between the results from these experiments. The erratic behavior of S1 and S2 can be explained from Fig. 41. This is due to the falling/not falling of direct sun rays on a particular light sensor. Thus, S1 was shielded from direct sun at the 90-deg. position while S2 came into direct sunlight at the 30-deg. position. This attempt at normalize between experiments proved unsuccessful in the end, possibly due to the variation in sky and ground visibility at different rotations of the model space.

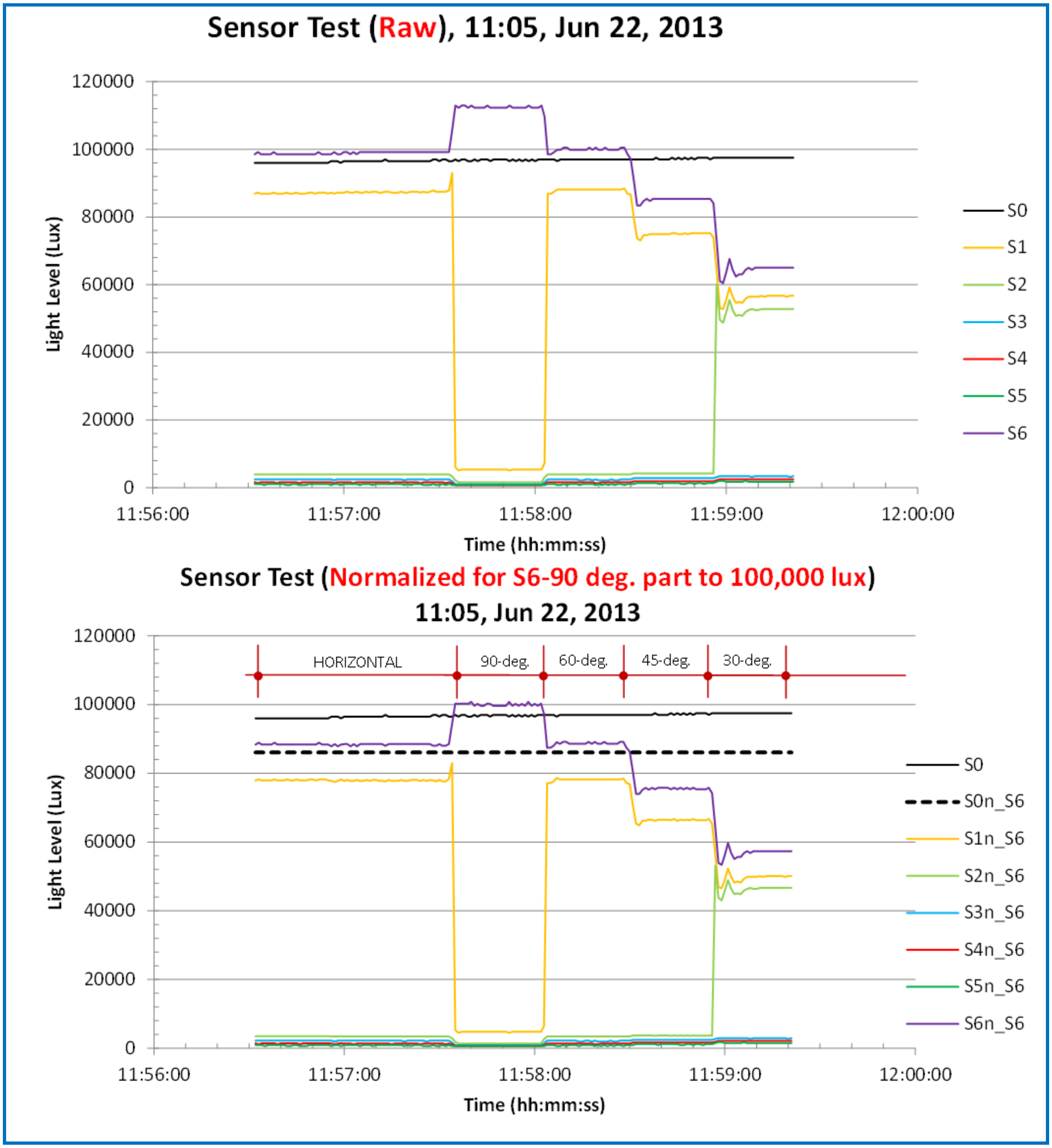


Fig. 40 Raw data (top). Same dataset normalized for the 90 degree segment of S6 (bottom)

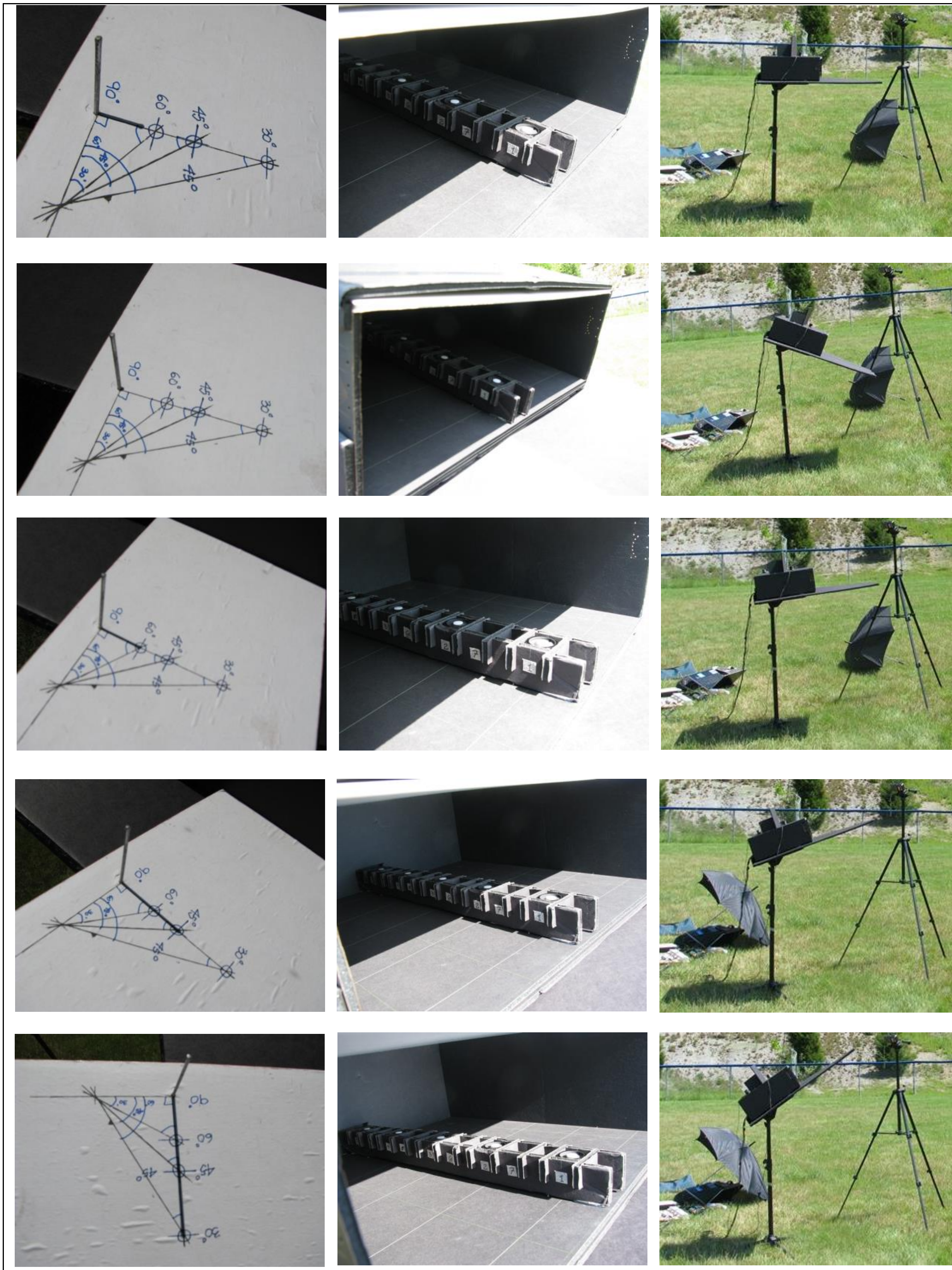


Fig. 41 Direct sun penetration at 90, 60, 45 and 30 degrees tilt of the model.

4.2.5.4 Repeatability of Results from Individual Single Sensor

In order to look for repeatability of experiments, an additional attempt was made to compare the results from individual sensors as derived from five different tests spaced few minutes apart. If repeatability could not be achieved between experiments carried out so close to each other it would be impossible to achieve when experiments are days apart or carried out at multiple locations.

On June 22, 2013, between 11:05 and 11:30 am, five tests were made with the setup in Fig. 26. The graph in Fig. 42 shows the results from sensors S6 and S2 for these five tests. In these tests the control sensor on top of the model roof (S6) has been normalized for the 90-degree portion of the data when the direct sun was falling perpendicular to the model base

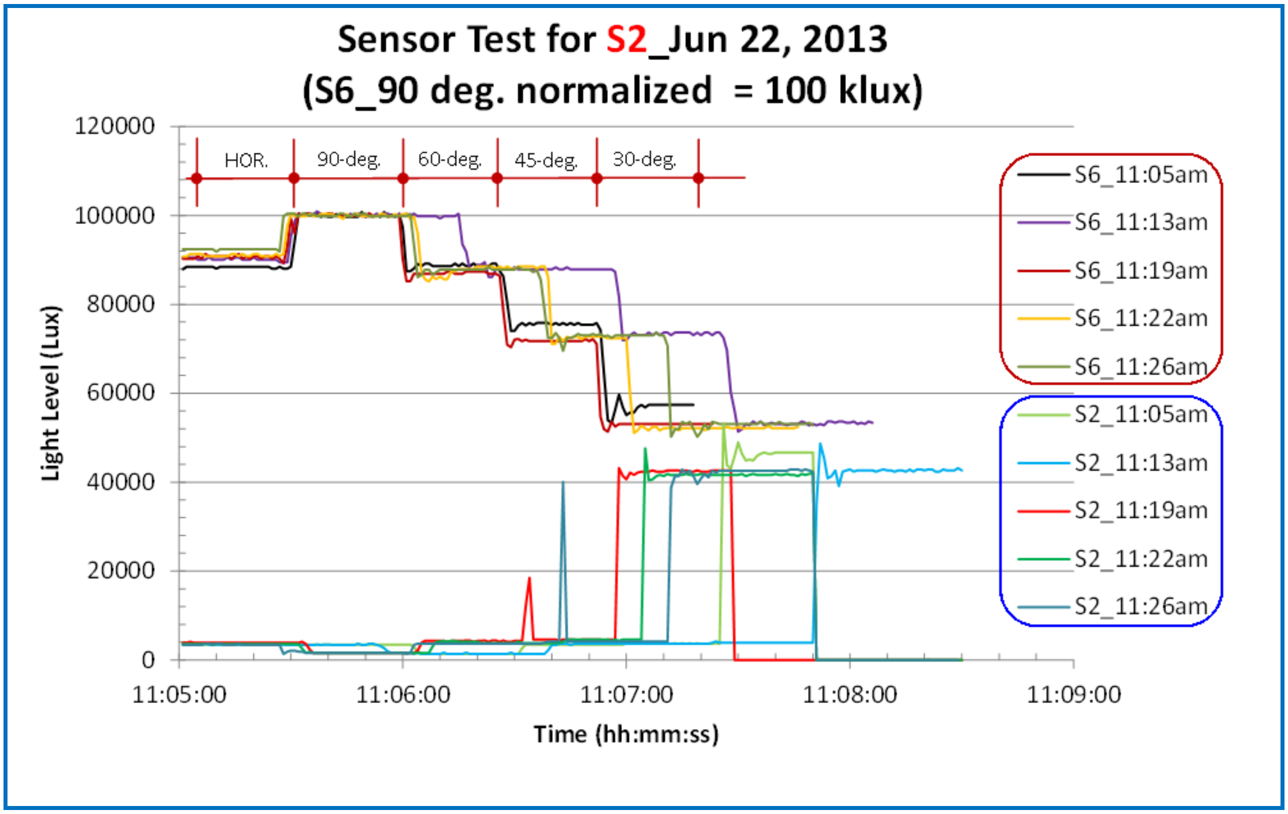


Fig. 42 Looking for repeatability in S2 (the second sensor inside the model).

In Fig. 43 (top) a magnified view of the bottom part of the graph in Fig. 42 is shown. One can see that for the interior sensors (S2 in this case) the resolution of the sensor is low, making data points very close to each other. A second batch of five experiments, between 12:30 and 12:50 pm was done that same day, after enhancing the resolution of the interior sensors (S1-S5) twenty-folds by adjusting the gain factors of the UTA amplifiers as described earlier. In Fig. 43 (bottom) we see a magnified view of this repeated experiment, using the same sensor (S2), now with a much better granularity.

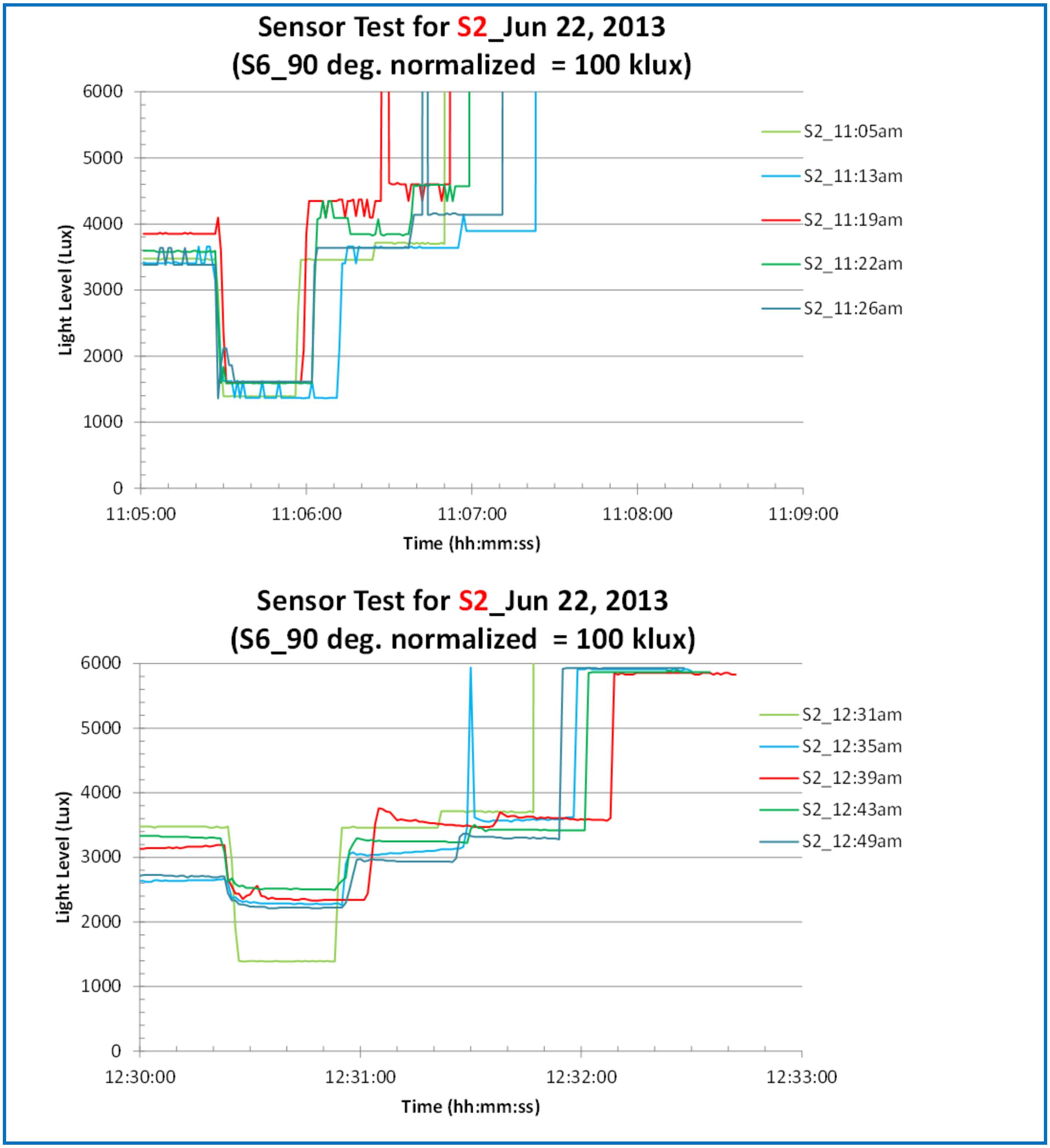


Fig. 43 Magnified Fig. 42, before gain factor enhancement (top) and after (bottom).

There was a bit of a change in the sky condition between the two sets of experiments, as seen in Fig. 28 and Fig. 29. The open end of the model space allowed direct sunlight to enter different depths of the interior space depending on the tilt of the model (Fig. 41).

A comparison of data from five experiments for interior sensors S2-S5 at higher resolution is shown in Fig. 44. Spikes (1) that are out of scale for these graphs, particularly at lower sun angle, are from direct sunlight hitting the sensor. The 12:31 pm experiment (2) is measuring consistently higher – perhaps there was a sudden increase of ambient light at this point. The general observation is that the readings from the individual sensors are varying within a range of about 500 lux (3) in the five experiments carried out in less than 20 minutes, probably due to a variation in ambient light level.

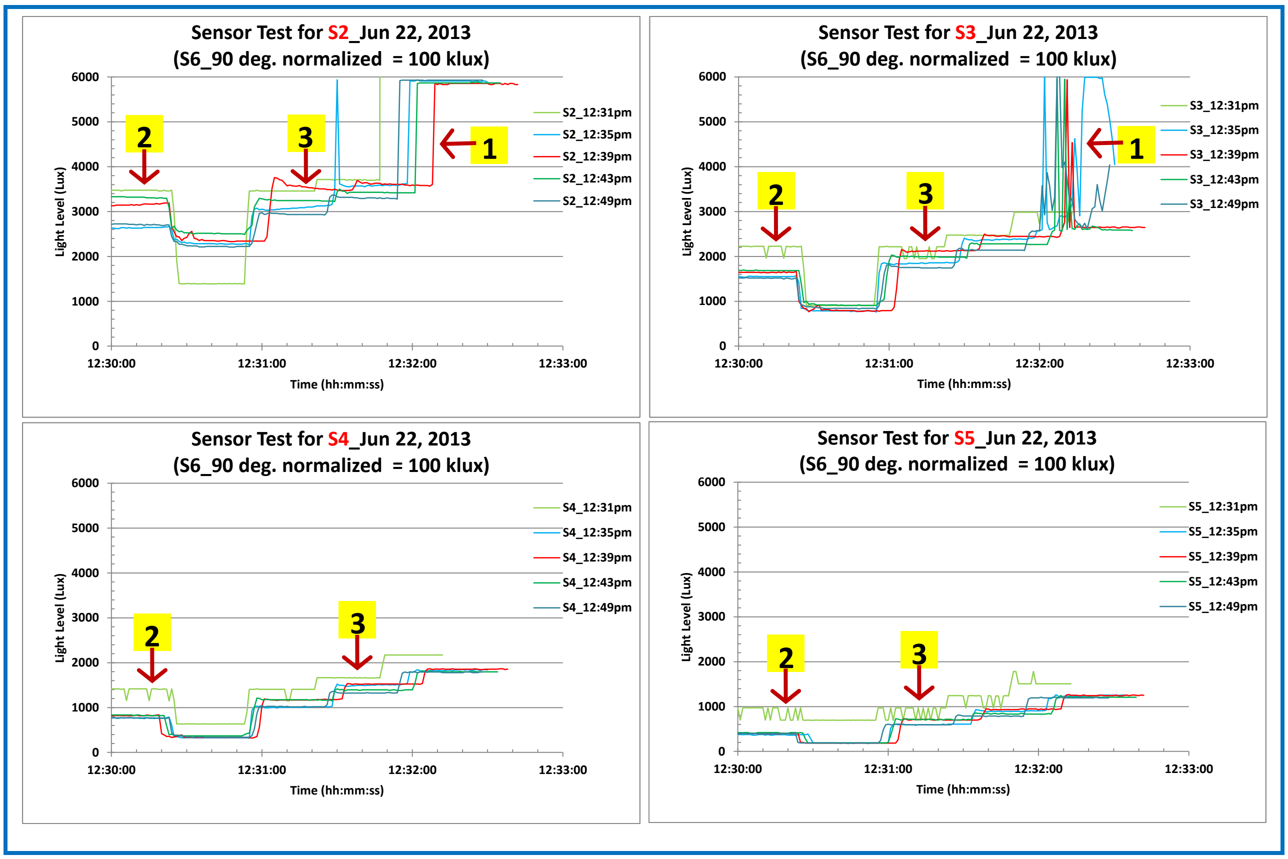


Fig. 44 Data from individual sensors S2-S5, from five experiments within 20 minutes.

4.2.5.5 Consistency of Ambient Light Level Measurement

As the model is rotated from a horizontal position through 90, 60, 45 and 30 degrees there is a drop in ambient light level as recorded by sensor S6, positioned on top of the model roof. This is shown in Fig. 45. It is seen that there is a fairly close match in the percentage of drop in the ambient light level between these two sets of experiments.

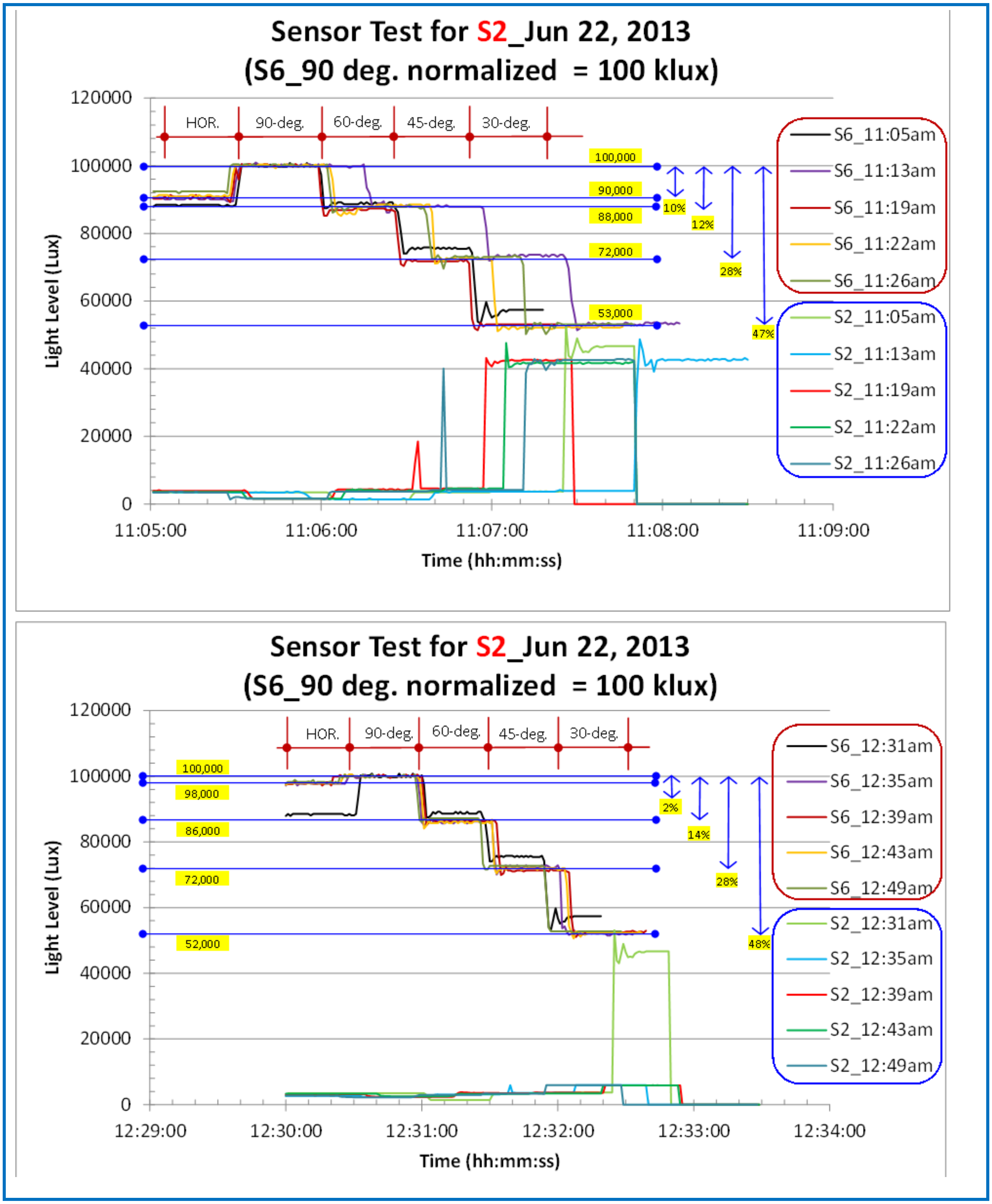


Fig. 45 Drop in ambient light level due to tilting of the model for S6.

4.2.5.6 Percentage Change in Individual Sensor Readings

The data from four experiments between 12:35 and 12:49 pm are compared to see the percentage change in individual sensor readings (Fig. 46 and Fig. 47). The first experiment of this set, starting at 12:31pm was left off this comparison because of its much higher values. Percentage of variation between the highest and the lowest number was calculated relative to the higher number. Significant variations in individual sensor readings are observed in these graphs.

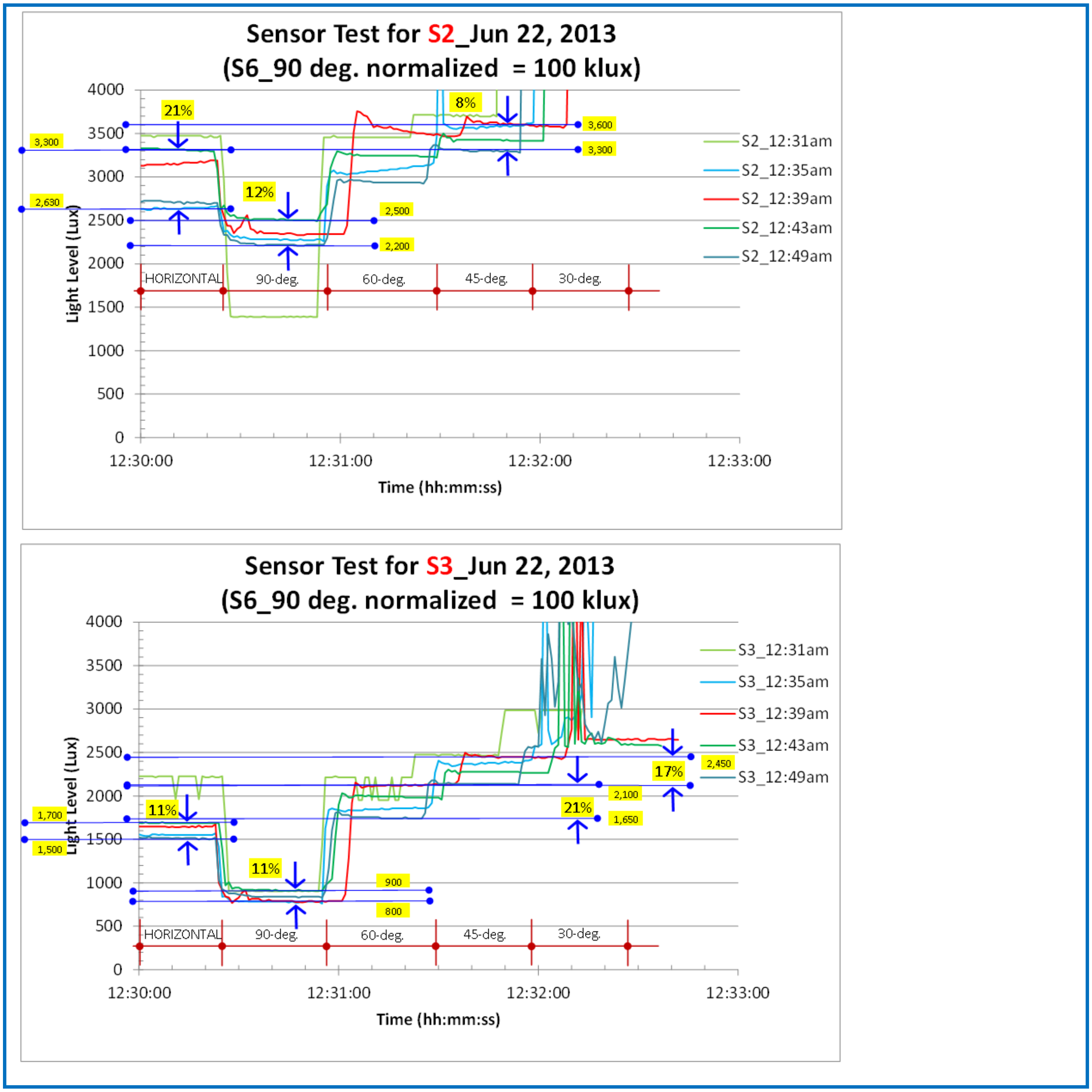


Fig. 46 Percentage change in four experiments for S2 (top) and S3 (bottom).

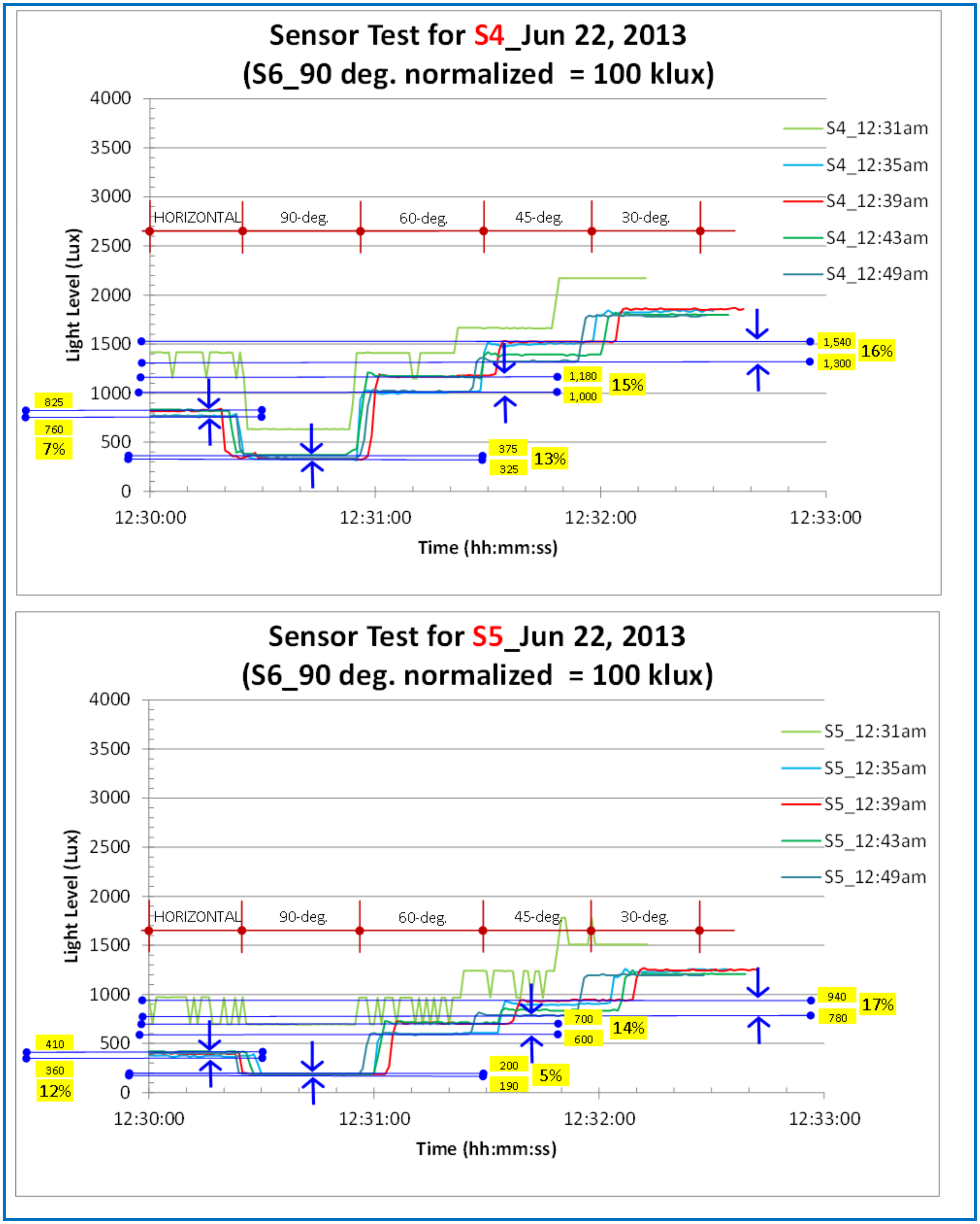


Fig. 47 Percentage change in four experiments for S3 (top) and S4 (bottom).

4.2.6 Conclusions from a year-long experimental effort at VT

- The experimental studies have failed to produce replicable results despite 'normalization' of the data in an attempt to eliminate the effect of variation in incident sunlight.
- Even a small amount of clouds in the sky seems to affect the results substantially. Normalization of the results could not eliminate the effect of cloud cover variation.
- It has been a challenge to find completely cloudless, sunny skies on a regular basis, introducing much delay between experiments. It was difficult to repeat experiments at the same times of a day, every day, to ensure the same 'horizon' for the model setup. One can achieve the sun angle of a previous experiment by rotating and tilting the model-base but this would introduce a different 'horizon' for the model each time, introducing significant difference in ambient lighting conditions.
- Given the large number of experiments called for by the parametric investigation of light shelves in this research, it is not feasible to complete this research without access to an artificial sky that can provide constant ambient lighting conditions – an experimental setup that is currently not available.
- The performance of a light shelf in real life is very much affected by the day-to-day fluctuation of ambient sunlight due to changing sky conditions. Even if access to an artificial sky could be arranged it would not be easy to correctly replicate such a huge range of diverse ambient lighting conditions representing a specific geographic location.
- From the above experimental findings it was concluded that the more practical approach to be employed for this research was to shift the methodology to climate-based simulation. This would allow climatic variation of a place to be properly reflected in the investigation while allowing a large number of experiments, representing numerous parametric variations, to be conducted in a reasonable amount of time.

4.3 Simulation Studies

4.3.1 Daylighting Simulation for this Research

This research needed a tool that can compare the daylight performance variation between numerous light shelf configurations for different time-periods, i.e. annual and seasonal. A tool that allows parametric study of multiple variables in a light shelf was therefore necessary. Grasshopper, a plugin for Rhinoceros was found appropriate for this task as it provides graphical programming interface to the daylight software DIVA for Rhino. Iterative simulation loops representing multiple climatic variations, time periods and light shelf variables could thus be easily set up and run for the needed results.

In order to manage a large sample of simulation results one needs to utilize an optimization tool. The systematic literature review pointed to several such tools. One of the options explored was the use of 'Galapagos,' an 'evolutionary solver' that can easily plug into the grasshopper script used for simulation in this research. However, it was found difficult to make Galapagos converge to a small set of solutions within a reasonable amount of time (Fig. 48)

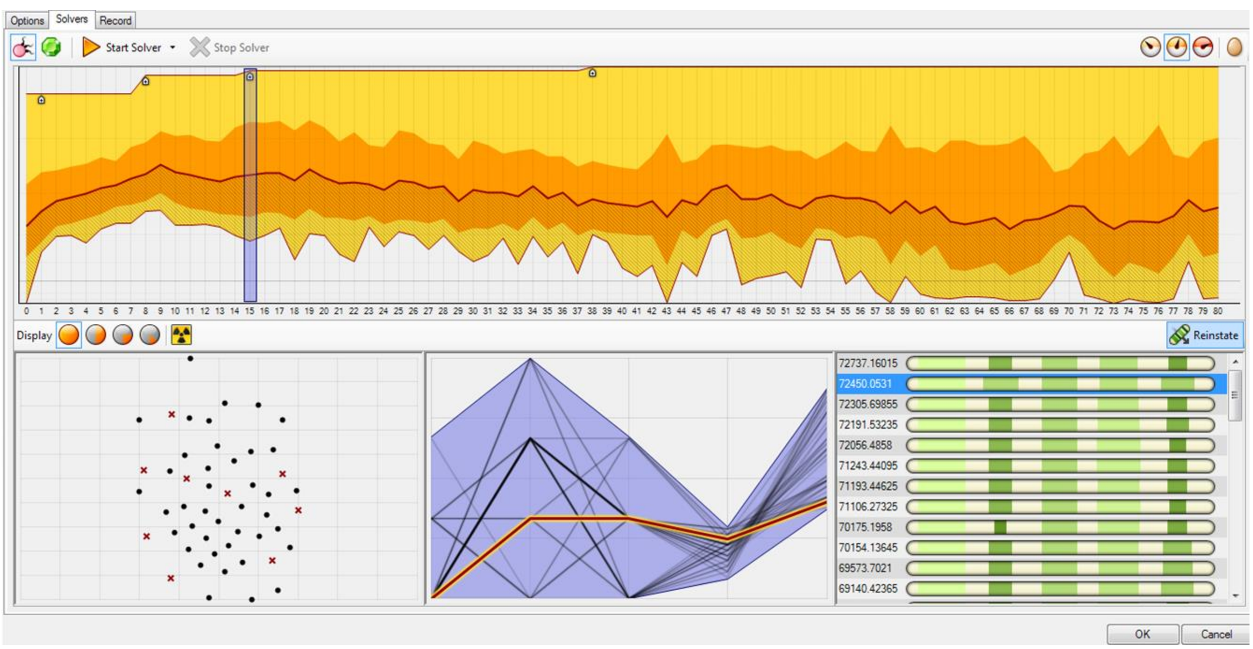


Fig. 48 The Galapagos evolutionary solver was tested as an optimization tool.

In case of the present research, it became apparent that the number of light shelf variations needed to be analyzed for constructing a proof of concept was initially not significantly high. Since light shelves options for this study were considered to be manually adjustable to predefined positions with simple tools by the average user, it limited the number of parameters that were practically feasible. Therefore, an automated simulation loop was designed for this research, using DIVA4Rhino and Grasshopper. This allowed unsupervised simulation of all possible light shelf combinations that were needed for this research. Thus, the optimization strategy finally utilized for this research was that of 'brute-force search or exhaustive search, exploring the full set of all possible pre-defined options (Wikipedia, 2014).

The literature search revealed that many performance metrics were in use for daylight performance. Of these, one of the more recently developed metrics, 'Daylight Availability' was chosen to be used in this research (Fig. 49). This is a climate-based, dynamic daylighting metric, which uses Typical Meteorological Year (TMY) weather data to calculate daylight performance at a specific geographic location taking local climatic factors into consideration. Daylight Availability is expressed as 'percentage of the occupied hours of the year when a minimum illumination threshold is met by daylight alone'(C. F. Reinhart & Wienold, 2011).

35	65	65	83	79	74	79	75	66	48	42
24	43	70	46	62	65	80	63	57	39	39
69	66	79	78	80	81	80	81	77	71	63
83	78	82	83	88	89	85	81	83	83	83
86	88	92	92	93	92	92	90	91	88	86
93	92	97	96	97	97	98	96	94	94	92
98	98	98	99	100	100	100	100	99	98	97
98	100	100	100	100	100	100	100	100	100	99
100	100	100	-6	-12	-10	-11	-11	100	100	99
100	-14	-21	-14	-20	-18	-19	-20	-20	-16	-5
75	79	65	64	61	61	61	62	65	74	74

Fig. 49 Performance matrix - Daylight Availability.

4.3.1.1 Model Setup and Parameter Investigation

A 30'x 30' open-plan office space was chosen for simulation in this study. This space was considered to be on the ground plane with no other external obstructions surrounding it. An opening, spanning the entire width of one side of the space, with a sill height of 3'-0" brought daylight into the space. A manually adjustable light shelf within this opening modulated the daylight coming indoors. The parameters associated with this study space were as follows:

1. Space Geometry:
   a. Width x Depth x Height: 30' x 30' x 10.5'
   b. Window Opening: 30' wide x 7' high with a sill height of 3'
2. Light Shelf Geometry (manual adjustment options):
   a. Rotations:
      i. 0-degree
      ii. 15-degree

iii. 30-degree and
iv. 45-degree

b. Heights:
i. 6 ft.
ii. 7 ft.
iii. 8 ft. and
iv. 9 ft.

c. Depths:
i. 2 ft.
ii. 4 ft.
iii. 6 ft. and
iv. 8 ft.

3. Reflectance:
   a. Ground Plane: 20%
   b. Walls: 50%
   c. Floor: 20%
   d. Ceiling: 80%
   e. Light Shelf: 90%

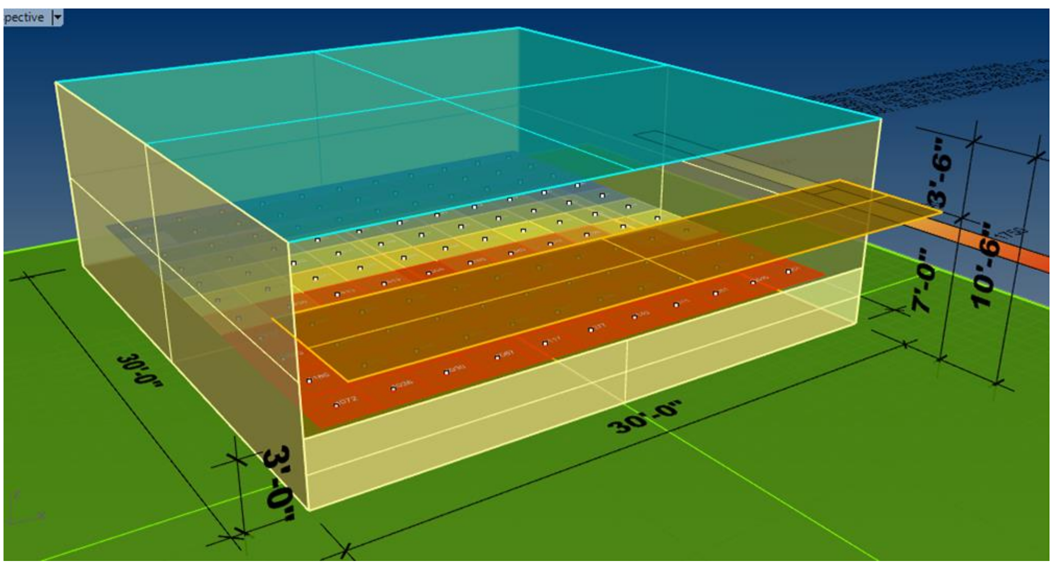


Fig. 50 Simulation Model Baseline Geometry

4.3.1.2 The Simulation Work-Flow

DIVA for Rhino, one of the daylight performance assessment software, originally developed at the Graduate School of Design (GSD), Harvard University, was used as the simulation engine for this study. DIVA for Rhino is based on RADIANCE and DAYSIM engines, both of which have been validated in many studies (Jakubiec, 2012). Grasshopper, a plugin for Rhino, was used to visually program the simulation runs to allow parametric studies of the light shelf variables, i.e. the change of rotation, height, depth, orientation and location. The

Grasshopper routine was designed to output the simulation results directly into an Excel spreadsheet for further post-processing. The general workflow of the simulation run is illustrated in Fig. 51. Additional information about the various components of the simulation engine and how they function is given in Appendix-A.

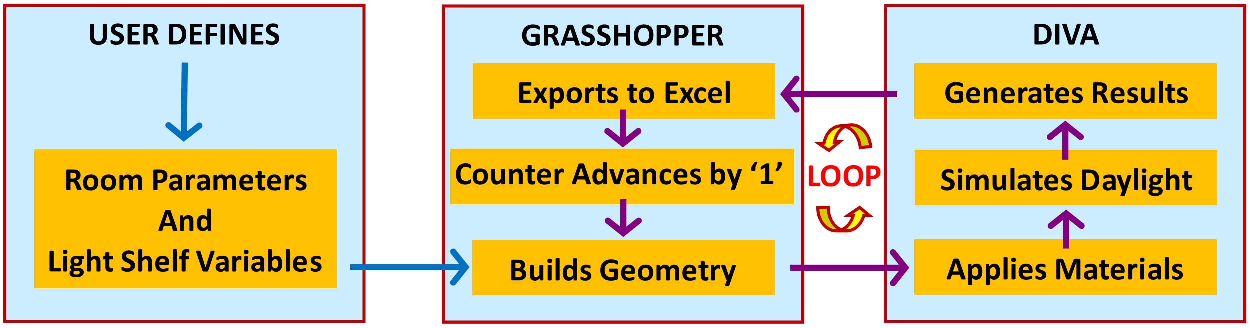


Fig. 51 Work-flow of the simulation engine

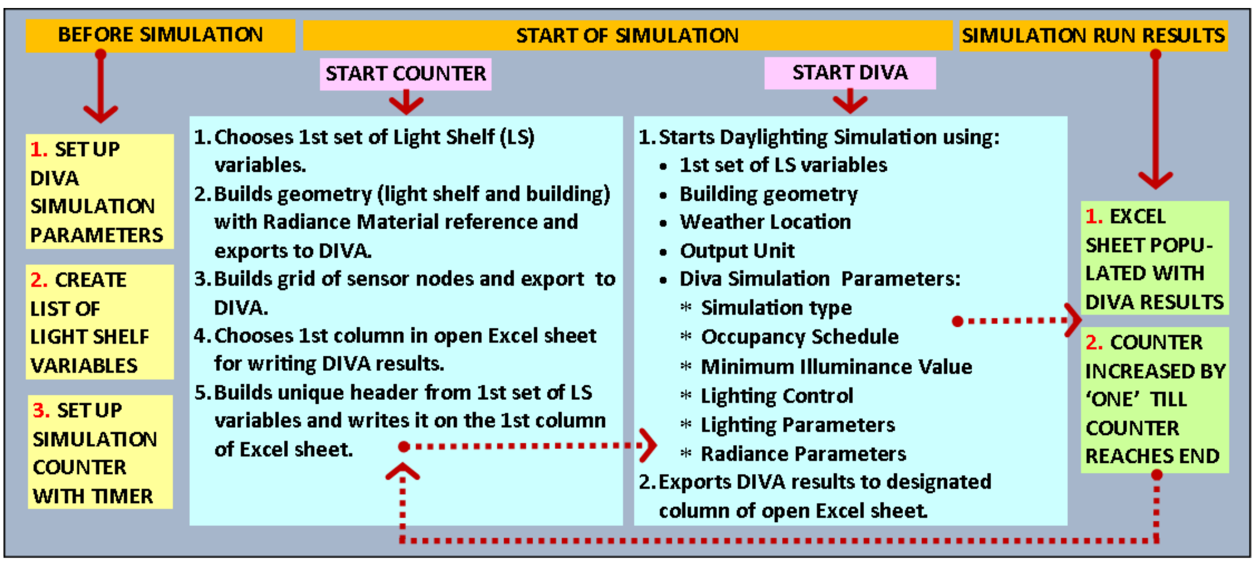


Fig. 52 Detail of the simulation loop

The working of the simulation engine is illustrated in greater detail in Fig. 52. Before simulation began the user had to setup three things: (1) a set of DIVA simulation parameters, (2) the room geometries and light shelf variables and (3) a counter/timer for the simulation engine. The DIVA parameters included, amongst other things, the geographic location for the simulation (to apply the appropriate climate data), the material characteristics of the geometries used, the format for the output and the lighting characteristics of the simulation context. The room geometry and its luminous characteristics used in this research have been described in an earlier section. For light shelf variables, this research chose three parameters, i.e. rotation, height and depth. Each one of these was varied for four settings, resulting in a total of 64 light shelf combinations (4x4x4). Once the simulation began, each one of these 64 geometries was taken up one by one and their daylighting performance evaluated. The counter/timer component of the setup provided the simulation engine the sequence number of the light shelf combination to be in acted upon at any instance. It also introduced a user-definable delay (5-second in this case) between two sets of performance evaluations to keep them distinct from each other.

The simulation began with the user starting the counter/timer followed by starting the DIVA simulation component within the delay time set up earlier. Triggering the counter/timer would: (1) generate the building and light shelf geometries, (2) create the grid of sensor nodes for light measurement, (3) build a unique header text and write it to an appropriate column of an open Excel file where the performance results from this run of simulation would be recorded. If the DIVA component was not started within the delay-time prescribed earlier, the counter would proceed to do all of the above for the following sets of light shelf combination until it senses the DIVA calculations to be in motion. Once the DIVA simulation component is triggered it uses the room and the first set of light shelf geometry, in addition to all other performance parameters setup for it earlier, to calculate the daylight availability (DA) results for this instance. Lastly, these performance results are exported to the designated column of the open Excel file setup by the counter/timer earlier. The completion of this export function is sensed by the counter/timer component which now advances to the next sequence until all combinations have been exhausted.

In the case of simulation runs where four seasons were involved, four DIVA components were used in parallel, each with its own Excel writer. Calculations would move from one DIVA component to the next, saving each season's results in a separate sheet of the open Excel file. A unique sheet numbers was specified in each of the four Excel writers before simulation began. Each of the four DIVA components used in this scenario referenced unique, user-defined, occupancy schedules, which related to the four seasons defined in this research. This is how the program allowed unsupervised simulation of all four seasons at the same time. As with the light shelves, the orientation of the room was also setup as four variables referring to the four cardinal directions of south, east, north and west. Unsupervised simulation was, therefore, made possible for the four orientations as well.

4.3.1.3 The Simulation Engine Configuration

- The seeds of the simulation engine used in this research came from 'Parametric Façade Optimization using Rhino-Grasshopper-DIVA-Galapagos' tutorials, developed by Jeffrey Landreth of CTL-E (http://performance-and-form.com/projects/parametric-facade-optimization-using-rhino-grasshopper-diva-galapagos/). To the initial tutorial file generously provided in their website this research added 'simulation-loop' and 'export to excel' functionalities, among other changes, as shown in Fig. 53.

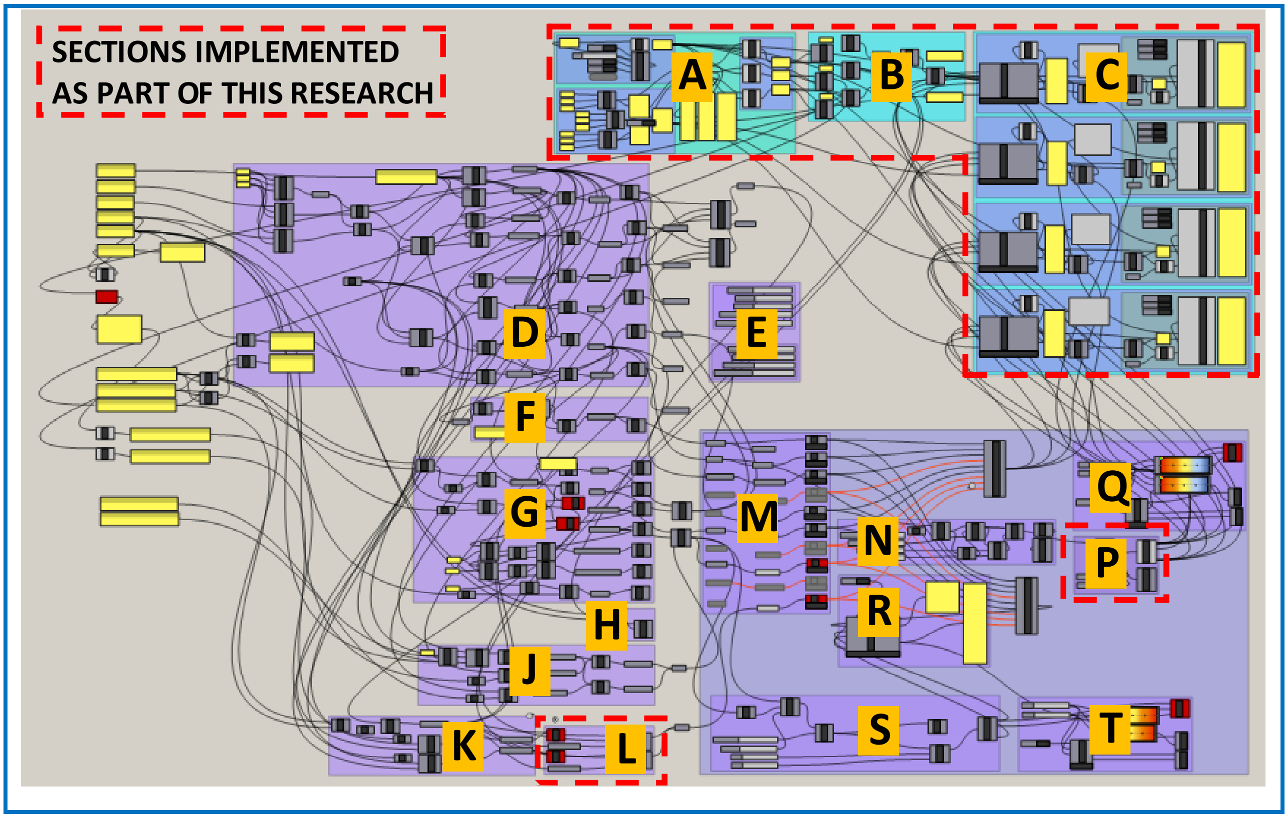


Fig. 53 Over view of the simulation engine

The various components of the simulation engine are:

- A: Light shelf parameter input, Counter and Timer
- B: Excel column header generator
- C: DIVA simulation component and Excel writer
- D: Basic Room Geometry generator
- E: Basic Room Geometry input
- F: Ground Plane generator

- G: Window geometry generator
- H: Ceiling geometry generator
- J: Inclined ceiling-to-soffit generator
- K: Light shelf generator
- L: Light shelf rotation generator
- M: DIVA Materials Selection
- N: DIVA Results Grid Creation (illuminance)
- P: DIVA Grid Size generator (illuminanc)
- Q: DIVA Results Visualization (illuminance)
- R: Calculations and Results (irradiation)
- S: DIVA Results Grid Creation (irradiation)
- T: DIVA Results Visualization (irradiation)

In the list above sections A, B, C, L and P were specifically developed for this research. A detailed explanation of the first three sections is presented below.

Section-A (Fig. 54):

In this section the user defined the light shelf variables. The idea was to have a flexible system which would allow the user to input a wide variety of variables without having to tweak the system substantially. As each instance of each variable was taking about 3-minutes to simulate, it was imperative to have a system where the user could use fewer input and reap the benefit of a shorter simulation run if time, rather than detail, was the primary constrain. Once the users had given their input variables the system generated a list of all required combinations from the given variables and selected each combination in sequence to feed into the simulation run.

A second critical function of this section was that of a counter/timer. This allowed each simulation run to come to completion before a second run was initiated, advancing the column numbers in Excel by one after the results of each run was written. In summary, it can be said that the long, unattended simulation sessions, extending more than a week at times, that was required for this research, was made possible by the working of this section of the simulation engine. A detailed explanation of the various components of section-A is presented below.

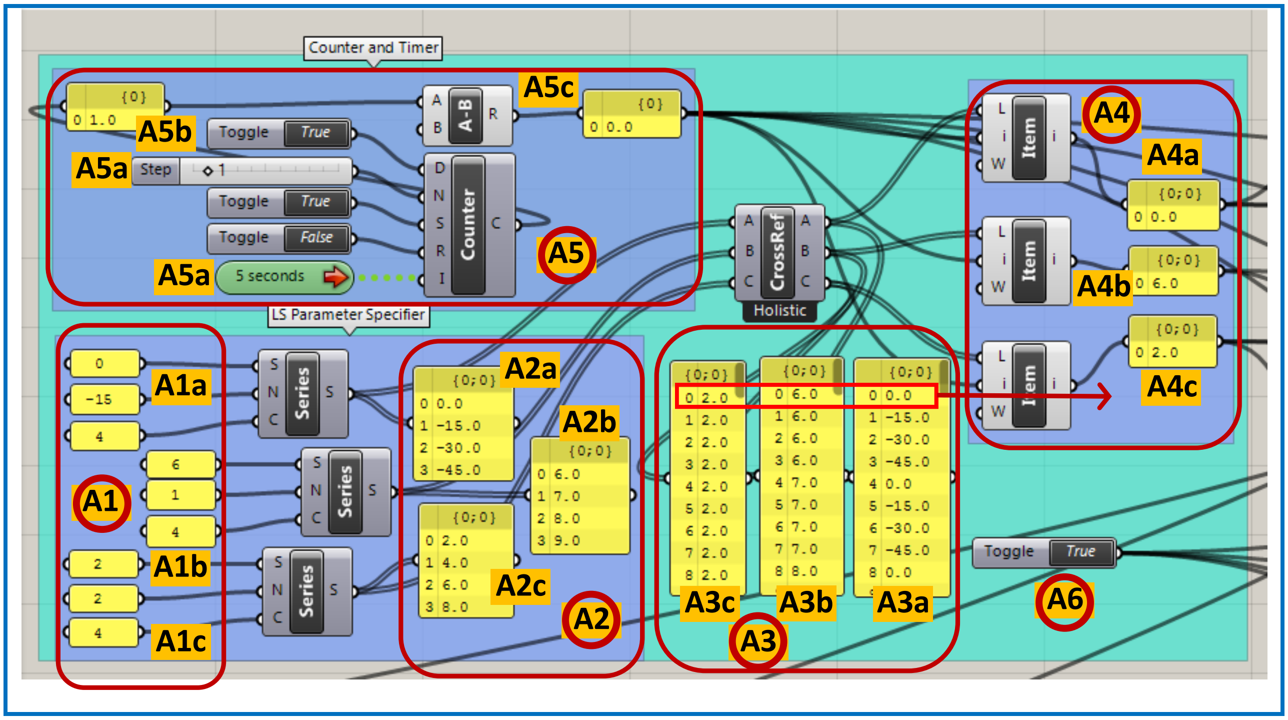


Fig. 54 Detail of Section-A of the simulation engine

- A1: This is where the user specifies the parameters for the light shelf. For this research only three parameters were used, Rotation (A1a), Height (A1b) and Depth (A1c). Each has three values associated with it: beginning value, increment and step-size. For example, in Fig. 54, bottom left corner, the set of values next to A1a (rotation) shows that the beginning position for the light shelf will be 'zero' degrees (horizontal) and the light shelf will be incremented each time by -15 degrees (clockwise, the outer edge moving upwards) for a total of 4 steps. Thus the four positions of the light shelf that the simulation will automatically calculate are 0, 15, 30 and 45 degrees from the horizontal. Similarly, the set of values above A1b (height) shows the beginning value to be 6 ft., incremented by one-ft. at every iteration for a maximum of 4 cycles. This generates light self at 6, 7, 8 and 9 ft. from the finish floor for simulation while A1c (depth) parameters generated are 2, 4, 6 and 8 ft.

- A2: This group shows the list of all variables for rotation (A2a), height (A2b) and depth (A2c).

- A3: There will be a total of 64 combinations (4x4x4) for the three parameters. A list of all 64 is made here beginning with the sequence number 0 (zero).

- A4: A light shelf parameter combination is assembled here from the three previous lists, beginning with sequence 0 (zero). This combination is sent to two places, (1) construct the geometry of the light shelf and (2) to create the header nomenclature for the Excel column that will record the simulation results generated from this light shelf combination.

- A5: The ‘Counter’ (from the Grasshopper plug-in Firefly) generates a number starting with ‘one’ (A5b) and increments it by ‘one’ each time a simulation run is completed. As the light shelf parameters list starts with sequence-0 (zero) this number had to be decreased by ‘one’ (A5c) in order to catch the first line of that list.

Section-B (Fig. 55):

An important function of this section was the generation of unique name-tags for each simulation variable that would be subsequently used to name each simulation run. The system, as designed, allows the user to design this naming convention to their preference. Next, it takes these name-tags and joins them together into one unique name that identifies each simulation run. These names are then sent to Excel to distinctly identify the results from each simulation cycle. The details of the components from this section are discussed below.

- B1: The suffix ‘R’, ‘H’ and ‘D’ are added to the values received from the previous section for rotation, height and depth respectively.

- B2: The full Excel column header is assembled here (B2d) and sent to Excel for use.

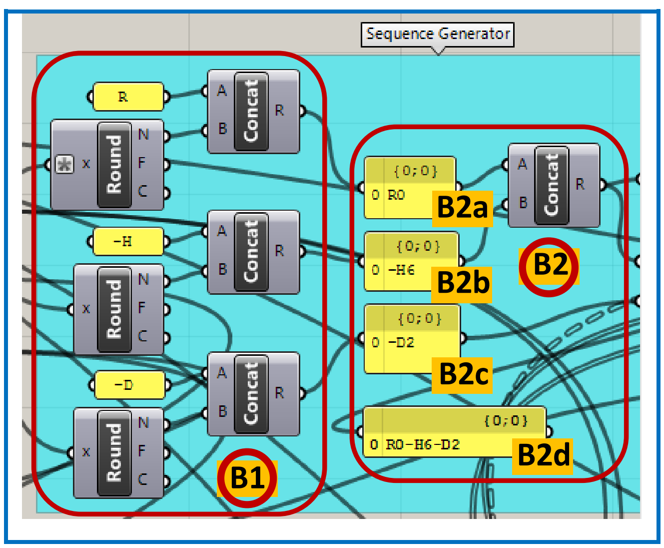


Fig. 55 Detail of Section-B of the simulation engine

Section-C (Fig. 56):

This section contains the heart of the program, i.e. the DIVA daylight simulation component. Here the user has the flexibility to choose the various simulation parameters such as location, time period and output format (Fig. 57). The various parts of this section are further described in the section below.

- C1: This has the main DIVA daylight simulation component (C1a). Based on the settings chosen, it generates, in this case, a list of daylight availability results that can be arranged as a matrix of values (C1b).

- C2: The Excel column-header text that came from an earlier step started with a sequence number of 0 (zero). This is increased by 'one' before it is sent to 'ColumnStart' input in the ExcelWrite component to ensure recording of this set of data in the first column of the Excel sheet.

- C3: This is the Excel writer ('ExcelWrite') component is from the Grasshopper plug-in LunchBox) which sends the simulation results generated by DIVA into an open Excel sheet which can be specified under the 'Worksheet' switch.

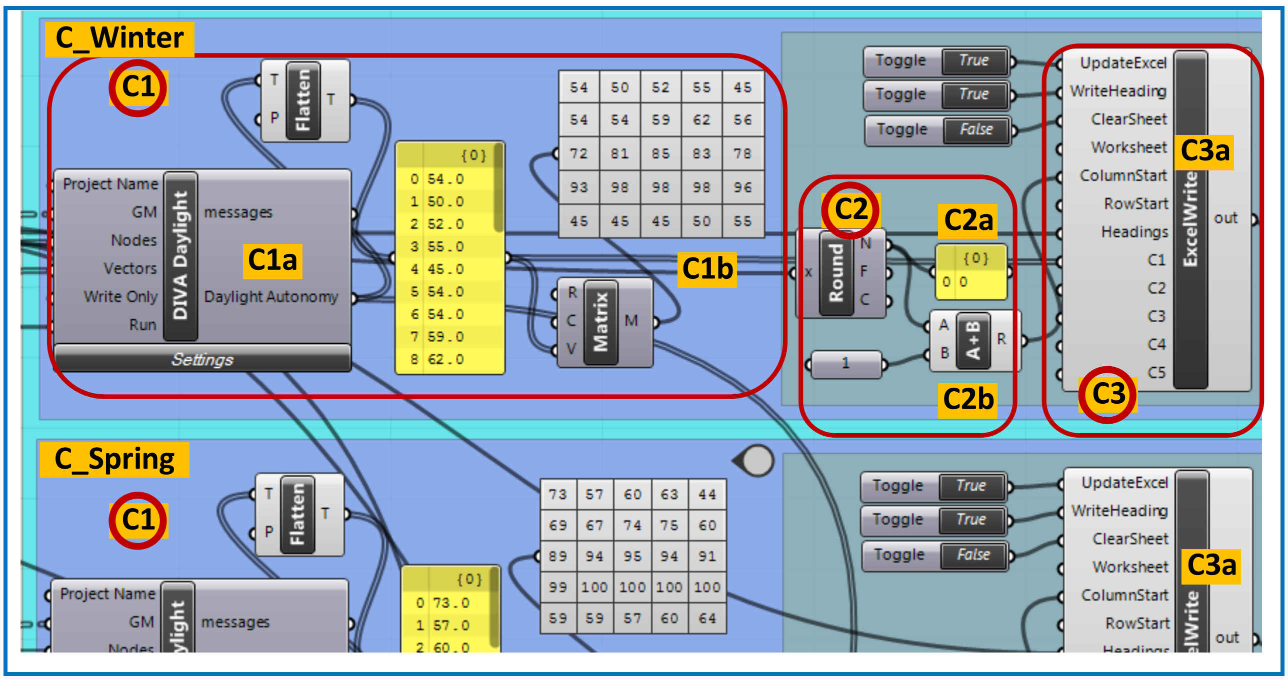


Fig. 56 Detail of Section-C of the simulation engine

The DIVA Settings (Fig. 57):

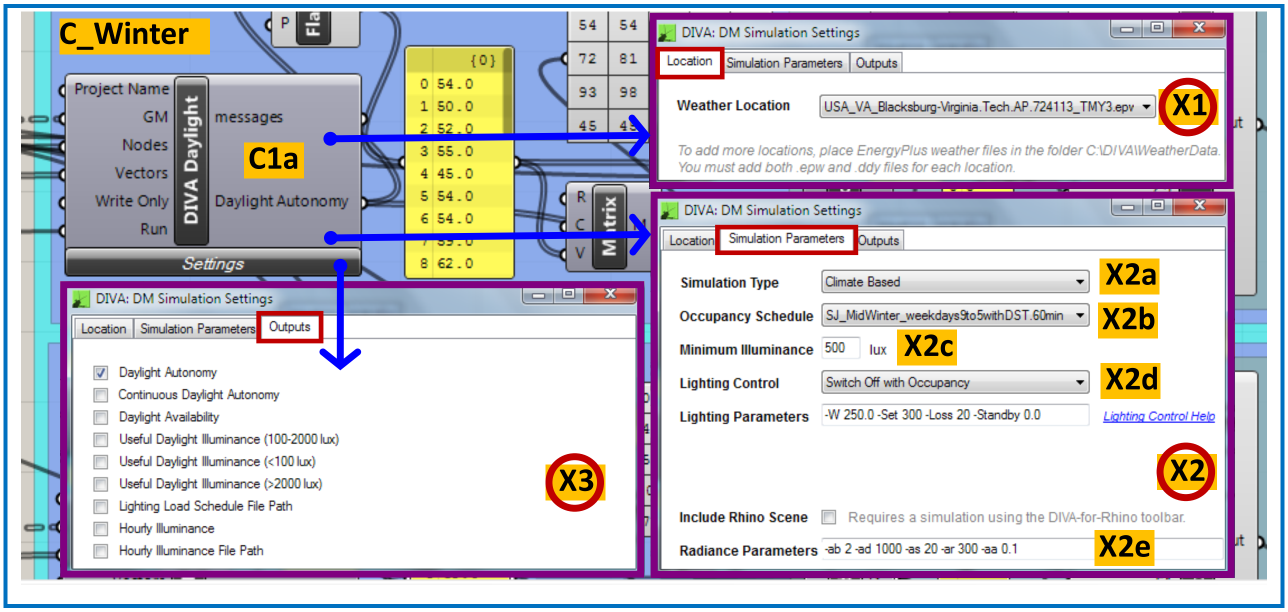


Fig. 57 DIVA settings for climate based daylight simulation

The DIVA daylighting simulation component has three tabs for its settings: Location (X1), Simulation Parameters (X2) and Output (X3). For this research the Simulation Type (X2a) is 'climate-based' and the Minimum Illuminance (X2c) is 500 lux. The Occupancy Schedule (X2b) is an Excel file in 'Computer>Local Disk (C:)>DIVA>Schedules' which determines the 'occupied hour' DIVA will use to calculate the daylight availability results. For this research, the seasonal daylight calculations were achieved by using separate Excel occupancy files for each season.

Exporting DIVA results automatically to Excel (Fig. 58):

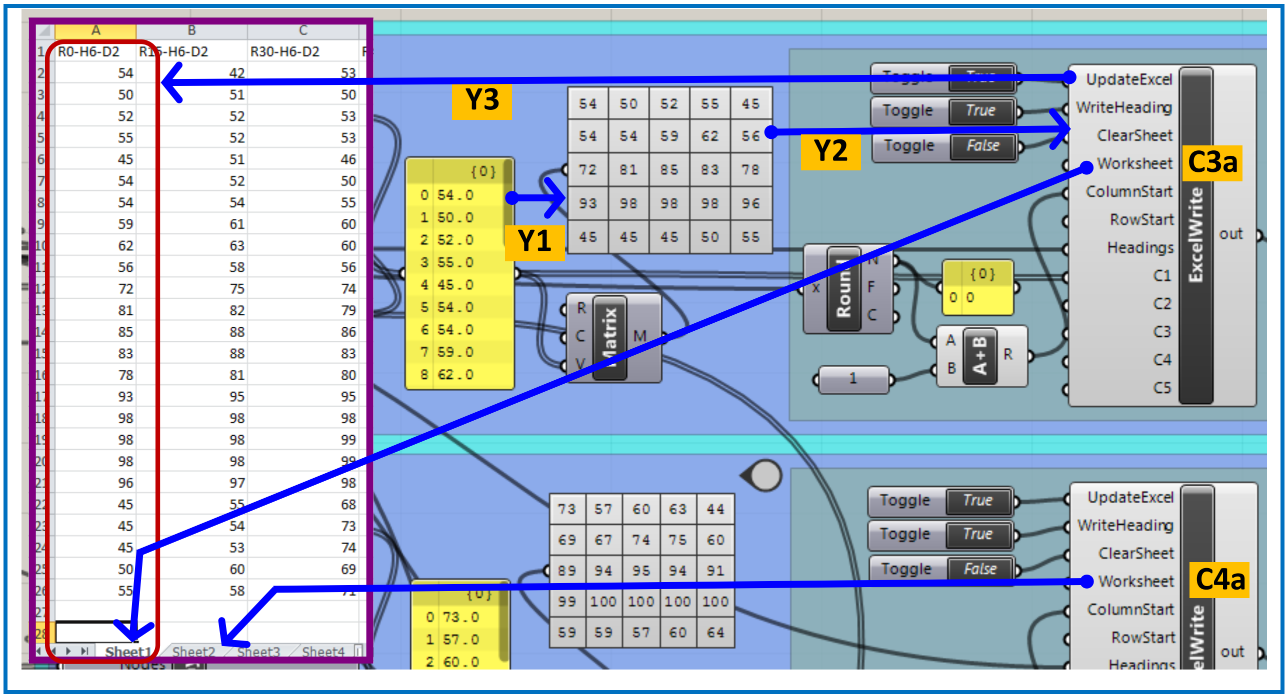


Fig. 58 Automatic export of DIVA simulation results to Excel

In the ‘Worksheet’ channel of the ‘ExcelWrite’ grasshopper component on can specify a sheet number in the open Excel file where the DIVA results will be written. For this research with four seasonal calculations, four DIVA components, each with its own Excel writer was set up in parallel. Each one of these four Excel writers referenced one unique sheet in the open Excel file. Thus, for example, in Fig. 58, the top writer (C3a) was accessing sheet-1 while the bottom writer (C4a) was accessing sheet-2 of the open Excel file. In this example one can see how the output from DIVA is visualized in a 5x5 matrix (Y1) and sent to the Excel writer (Y2) to be recorded in column form in an open Excel file (Y3).

4.3.1.4 Analysis of Simulation Results

The simulation results generated by the DIVA daylighting performance software for this research and recorded in Excel were in the form of Daylight Availability (DA). The post-processing these results to make performance comparison between multiple light shelf configurations involved several steps: (1) Defining base-case for comparison, (2) Sorting DA values into three categories of under-lit, well-lit and over-lit and finally (3) expressing the performance of to light shelves as a single number for ease of comparison.

Selection of 'Base-Case'

In making performance comparison between various light shelf configurations one needed a bench mark or 'base-case' to compare them against. Therefore, for the assessment of the benefit of 'fixed' light shelves, one that remains in the same position all year round, 'no light shelf' or the absence of any light shelf was used as the 'base case' (Fig. 59). For performance evaluation of seasonally adjustable light shelves, the performance of the 'annually optimum fixed light shelf' for a particular season was used as a point of reference when assessing the best adjustable light shelf for that season. To find the best adjustable 'segmented light shelf' on a seasonal basis the best adjustable 'simple light shelf' for that season was used as the 'base case'. For example, in the case of Blacksburg, VA, the best annually optimal fixed light shelf for the south orientation was found to be of the configuration R0-H6_D8 (Rotation=0°, Height=6', Depth=8'). In assessing the best seasonally adjustable light shelf for Blacksburg, VA for south in winter the performance of R0-H6-D8, *for the duration of the winter season*, was taken as the base case. Similarly, light shelf configuration R15-H9-D8 was found to be the best seasonally adjustable light shelf for winter in the south orientation of Blacksburg, VA. Therefore, to assess the performance of segmented adjustable light shelf for south orientation in Blacksburg this light shelf was taken as the base case for comparison.

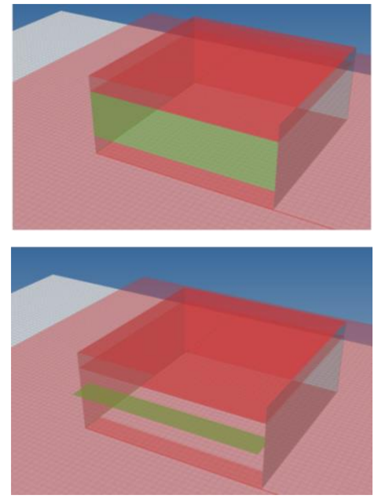


Fig. 59 'No light shelf used as 'base-case' for 'fixed light shelf).

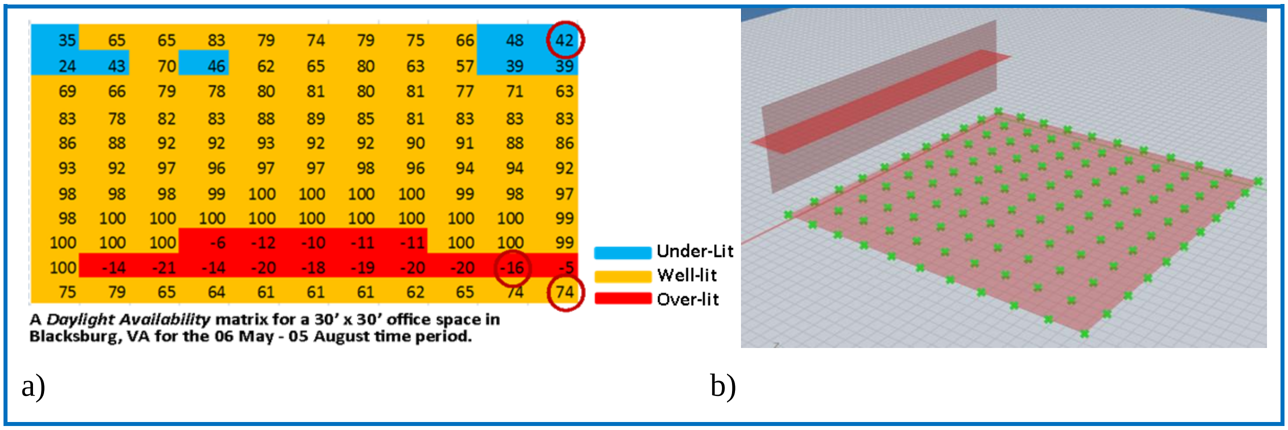
Daylight Availability Numbers Sorted Into Three Categories

'Daylight Availability,' (DA) one of the dynamic, climate-based daylight evaluation metrics, was used in this research to compare the performance of the various light shelf configurations. The test-room used in this research had a matrix of 121 (11x11) sensor nodes measuring illumination at the working height of 2.5 ft. (Fig. 60, b). Each simulation run, representing one set of light shelf parameters, therefore, generated a set of 121 DA values, one value at each node. For the purpose of this research each set of these 121 DA values were sorted into one of three categories:

- Under-lit: 0-49 DA
- Well-lit: 50-100 DA

- Over-lit: Ten times (10x) the minimum threshold illumination (500 lux for this study) for 5% or more of the occupied hours. In the format of the Diva output, these numbers are given as negative numbers. Nodes which are over-lit for less than 5% of the occupied hours are also considered as well-lit (Fig. 60, a).

Next these three categories of DA values were used to help in the performance comparison of various light shelf configurations.



35	65	65	83	79	74	79	75	66	48	42
24	43	70	46	62	65	80	63	57	39	39
69	66	79	78	80	81	80	81	77	71	63
83	78	82	83	88	89	85	81	83	83	83
86	88	92	92	93	92	92	90	91	88	86
93	92	97	96	97	97	98	96	94	94	92
98	98	98	99	100	100	100	100	99	98	97
98	100	100	100	100	100	100	100	100	100	99
100	100	100	-6	-12	-10	-11	-11	100	100	99
100	-14	-21	-14	-20	-18	-19	-20	-20	-16	-5
75	79	65	64	61	61	61	62	65	74	74

a) b)

Fig. 60 (a) Matrix of DA numbers in 3-gourps and (b) an 11x11 matrix of sensor nodes

	A	B	C	D	E	F	G	H	I		BO	BP
1		R = Rotation	Light Shelf:	R0-H6-D8	R0-H7-D8	R15-H9-D8	R0-H8-D6	R0-H7-D6	R15-H9-D6	R1	R45-H6-D8	No LS_R0-H6-D0
2		H = Height	Node-1	70	67	40	17	68	39		18	43
3		D = Depth	Node-2	44	50	47	32	49	42		20	58
4			Node-3	56	50	53	36	48	66		32	62
121			Node-120	55	58	74	65	62	-5		-17	-27
122			Node-121	50	57	70	62	60	71		-14	-21
123												
124		Under-lit	Raw Number:	12	19	7	20	13	7		31	2
125		Well-lit	Raw Number:	80	72	68	64	62	61		21	47
126		Over-lit	Raw Number:	29	30	46	37	46	53		69	72
127			Total Nodes:	121	121	121	121	121	121		121	121
128												
129			Orig Seq:	49	53	62	41	37	46		52	
130			Annul Best:	1	2	3	4	5	6		64	
131			Light Shelf:	R0-H6-D8	R0-H7-D8	R15-H9-D8	R0-H8-D6	R0-H7-D6	R15-H9-D6		R45-H6-D8	No Light Shelf
132		Under-lit	Out of 100	10	16	6	17	11	6		26	2
133		Well-lit	Out of 100	66	60	56	53	51	50		17	39
134		Over-lit	Out of 100	24	25	38	31	38	44		57	60
135				100	100	100	100	100	100		100	100
136				Best	2nd	3rd	4th	5th	6th			

Fig. 61 Sorting DA numbers into three categories

As an illustration, Fig. 61 shows how the raw results from a DIVA simulation for annually optimal fixed light shelf, exported into excel, was subsequently sorted into three categories of DA values to facilitate comparison between light shelf performances. In this example Row1 lists the light shelf configurations while the column under each light shelf represents their respective 121 raw daylight availability numbers in rows 2-122. Rows 124-126 give the raw count of nodes in each of the three daylight categories, i.e. under-lit, well-lit and over-lit. Rows 132-134 converts these numbers into percent range for standardization between various DA matrix sizes. Next, Rows 132-134 were sorted left to right between columns D & BO (64 columns representing the 64 combinations of light shelf parameters) with the criteria of maximizing well-lit, minimizing over-lit and minimizing under-lit, in that order.

The numbers from row132-134 in Fig. 61 shows the best fixed light shelf combination to be R0-H6-D8 (row 1, column D), which has the highest well-lit and the lowest under and over-lit numbers amongst the 64 light shelf combinations compared in this example. This is a horizontal light shelf with a height of six ft. and a depth of eight ft. A separate simulation was run for a 'no light shelf' scenario (R0-H6-D0) with results recorded in column BP. It can be observed that the optimum fixed light shelf on an annual basis, when compared with the case of 'no light shelf', shows an improvement of 27 (66-39) points in the well-lit category. The optimum light shelf also reduces the over-lit points by 36 (60-24) although in the category of under-lit it is 8 points more (10-2) as compared to the 'no light shelf' base-case scenario.

Daylight Availability (DA) numbers for
No Light Shelf' in South, Blacksburg, VA

43	58	62	70	66	68	68	71	64	56	47
51	55	60	66	67	68	67	63	64	59	57
59	65	66	67	71	71	72	72	69	64	61
72	72	75	77	77	77	77	76	75	74	73
77	80	83	83	-7	-7	-8	84	-5	-6	-6
-7	-7	-9	-11	-11	-12	-11	-12	-11	-9	-11
-10	-11	-13	-15	-16	-21	-19	-19	-17	-16	-13
-14	-19	-23	-28	-32	-33	-33	-31	-29	-25	-19
-26	-36	-48	-53	-57	-58	-58	-55	-53	-43	-32
-39	-60	-68	-70	-72	-72	-72	-70	-70	-63	-45
-21	-25	-23	-22	-22	-22	-22	-23	-22	-27	-21

a)

Daylight Availability (DA) numbers for Optimal
Annual Fixed Light Shelf in South, Blacksburg, VA

70	44	56	55	58	67	66	65	55	55	41
42	54	55	53	60	64	51	44	57	38	44
50	57	54	61	63	68	65	64	63	53	46
58	65	68	72	69	69	72	72	70	71	62
69	71	75	75	-6	-6	-7	75	75	-5	-6
-6	-6	-7	-10	-9	-10	-10	-10	-9	-7	-9
75	80	83	83	83	-7	-5	82	-5	-6	-6
67	73	74	76	75	77	77	77	73	75	72
65	74	72	73	-6	-10	-7	-6	76	76	74
71	-11	-7	76	73	73	70	72	-6	-11	72
51	51	50	48	47	47	48	49	51	55	50

b)

NORTH

Legend:

- Under-lit
- Well-lit
- Over-lit

Fig. 62 DA numbers for the 11x11 matrix for south orientation, Blacksburg, VA

Another way of representing the DA numbers which has been sorted into three groups described above would be as a matrix on the horizontal plane of the sensor nodes in the test room. Such a matrix for a 'no light shelf' and an 'annually optimal fixed light shelf' scenario for south orientation of Blacksburg, VA is shown in Fig. 62a and Fig. 62b respectively. The figures illustrate the improvement in indoor illumination level due to the presence of light shelf.

Expressing Daylight Performance as Single Number

While the sorting procedure explained in the previous section did provide a method of performance evaluation for light shelves, an attempt was subsequently made to simplify the procedure further by expressing daylight performance as a single number. This was done by weighing the under-lit and over-lit numbers by a 'concern-factor' (Fig. 63). This impact factor would be chosen by the user and will allow for a more individual assessment of how bad the 'under-lit' and 'over-lit' conditions are perceived, relative to the activity envisioned for the space in question. In this research a 7-level concern-factor scale has been used, ranging from +1.0 to -1.0. A positive concern-factor adds credit for under-lit and over-lit values to the well-lit category while a negative concern factor penalizes the well-lit category by a certain amount.

Concern for 'Under-lit' & 'Over-lit'	Acceptable	Doesn't Matter	Some Concern	Avarage Concern	Big Concern	Severe Concern	Avoid
Concern Factor:	1.0	0.8	0.4	0	-0.4	-0.8	-1.0

Fig. 63 Concern Factor to modify 'Under-lit' and 'Over-lit' daylight categories

1	A	B	C	D	E	F	G	H
2	Applying 'Concern Factor' to Performance values for Optimum Annual Fixed Light Shelf (R0-H6-D8) in South Orientation, Blacksburg, VA:							
3	Concern Factor	Acceptable	Doesn't Matter	Some Concern	Avarage Concern	Big Concern	Severe Concern	Avoid
4	Under-Lit:	1.0	0.8	0.4	0	-0.4	-0.8	-1.0
5	Well-Lit:	1.0	1.0	1.0	1.0	1.0	1.0	1.0
6	Over-Lit:	1.0	0.8	0.4	0	-0.4	-0.8	-1.0
7		DAYLIGHT PERFORMANCE						
8	Under-Lit:	10	8	4	0	-4	-8	-10
9	Well-Lit:	66	66	66	66	66	66	66
10	Over-Lit:	24	19	10	0	-10	-19	-24
11	Daylight Index (DI):	100	93	80	66	53	39	32

Fig. 64 Expressing daylight performance as a single number using the 'concern factor'.

The use of 'concern-factor' on the performance values of optimum fixed light shelf configuration (R0-H6-D8) for the south orientation in Blacksburg, VA is illustrated in Fig. 64. Rows 4-6 show the concern factors while rows 8-10 give the performance values as divided into three categories of under-lit, well-lit and over-lit. Daylight performance is expressed as a single value in row 11 and is called 'Daylight Index' (DI) in this document. This is the summation of the three performance numbers that are listed immediately above the DI numbers.

In this example a concern-factor of +1.0 has been applied at the extreme left and -1.0 at the extreme right. This has decreased the DI value from 100 to 32. The idea is that, in the case on the left, the user may not be much bothered by the under-lit and over-lit areas of the space (acceptable/doesn't matter) for the intended use whereas, in the case on the right, having over-lit or under-lit parts in a space may be adversely affecting the use of that space (big-concern/avoid).

In the illustrated example the same concern-factor has been applied to both 'under-lit' and the 'over-lit' categories, expressing the users' equal preference/dislike for both of these categories. This may not always be the case. There may be scenarios, such as in a circulation pathway, where the under-lit areas of a room may be more of an annoyance than the over-lit areas or vice versa, such as in a dance-studio. Such nuances in daylighting preference can be captured in light shelf performance evaluation by applying appropriate concern-factor to the situation.

Some of the resulting benefits of this procedure are:

- Allows the daylight performance of a light shelf configuration to be expressed as a single number called the Daylight Index factor (DI).
- Allows for distinct sorting for optimization
- Enhances the DI (giving partial credit) from its median when the over or under-lit areas are considered as less of a concern while it
- Decreases the DI (penalizing it) from the median when these two categories are a reason for high concern.
- Incorporates user preference into the daylight performance matrix.

If one would prefer to compare the light shelf performance on a purely analytical level one can use the 'middle value' (average concern) as the modifying factor (where both over-lit and under-lit receives a factor of zero), thus comparing the scenarios essentially on the basis of the 'well-lit' fraction only. For the purpose of this research a concern factor of zero (average concern) has been used for the 'over-lit' and 'under-lit' fractions, thus comparing the various light shelf configurations primarily on their 'well-lit' fraction. However, in a real-life scenario of an interior atrium with vegetation, the concern-factor may well be +1.0, meaning that for the intended use of the space both over-lit and under-lit areas are not a problem. On the other extreme, a real life scenario of a private reading room may call for a concern factor of -1.0, meaning that both under and over-lit areas are to be avoided at any cost.

4.3.1.5 Discussion of Simulation Results

Simulation results are outcomes of mathematical models, which, by their very nature, are based on many assumptions. The closer these assumptions are to the reality, the better one can expect the simulation results to mimic the real world. While simulation results will never be able to completely resemble real world scenarios, they can be a good indicator in design direction, comparing performance in terms of individual parameter variations. In case of the present research one saving grace is the fact that the research is about comparison of the performance between different light shelf configurations. Since all tests are carried out using the same set of simulation assumptions, any error inherent in these assumptions affects all tests equally, making the comparative evaluation between tests still valid.

Improvement due to Annually Optimized Fixed Light Shelves

A number of system variables were investigated in this research to see the effect of their variations on interior illumination levels. For example, the first test-run of the simulation was done with only three system-variables (rotation, height and depth) to look at their effect on indoor daylighting levels (Fig. 65). The height of the light shelves investigated was at 6, 7, 8 and 9 feet above the finished floor level and the resulting illumination at a work-plane (30-inch above finish floor) was recorded. Once the same was done for all three system variables we had a total of 64 combinations (4x4x4) or 64 'sets of illumination data' to compare against each other for trends and patterns for one sample room at one constant orientation and location.

A light shelf often has an external and an internal section. Each of the above system variables was thus independently adjusted for the exterior and the interior sections in subsequent simulation runs. The 'rotation' of a light shelf, for example (Fig. 11), can have different values for the two sections of a light shelf – increasing the number of sets of illumination data by a factor of two.

Light shelf combinations
(4 setting for each of the 3 variables).

Rotation (R)	**0**	**15**	**30**	**45**
Height (H)	**6**	**7**	**8**	**9**
Depth (D)	**2**	**4**	**6**	**8**

4-STEPS: Total Combinations: 4 x 4 x 4 = 64

Fig. 65 Light shelf variables for 'proof-of-concept'

The first task addressed by this research was to re-evaluate the question, 'Do light shelves make any difference in the interior illumination of a space?' For an answer to this question, simulations were run with and without a light shelf present in the opening of the test space. .Simulation runs *with* the light shelf had the following range of variables:

- Rotation (4-variations): 0, 15, 30 and 45 degrees
- Height (4-variations): 6, 7, 8 and 9 feet from the finish floor
- Depth (4-variations): 2, 4, 6 and 8 feet, symmetrical between the outside and the inside

The resulting simulation run had sixty-four variations of the light shelf (4x4x4=64). Using the manual sorting procedure as illustrated in Fig. 61 the best light shelf combination for the four cardinal directions came out to be:

- South: R0-H6-D8
- East: R15-H9-D8
- North: R15-H7-D2 and
- West: R0-H7-D2 where R = rotation, H = height and D = depth.

Results from this simulation run are shown in Fig. 66, comparing the various light shelf combinations only on the 'well-lit' category. A similar comparison was made for Miami and Boston to see the results for different latitudes as shown in Fig. 67.

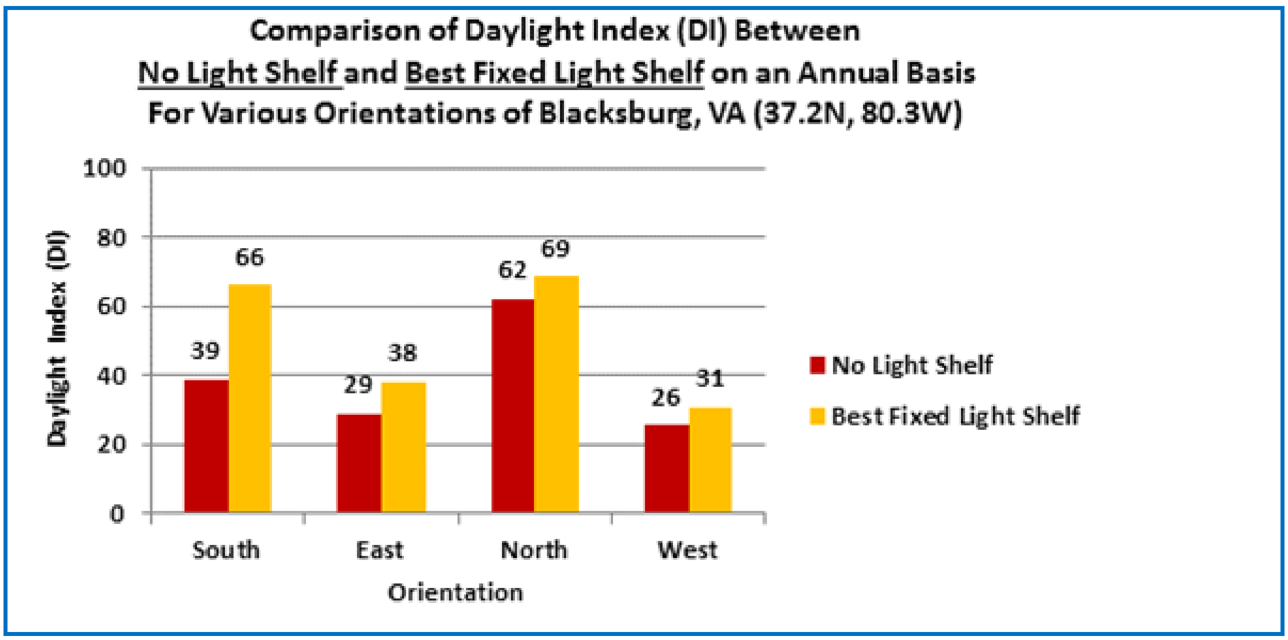


Fig. 66 Light shelf in Blacksburg: 'no LS' & 'fixed LS' in terms of 'well-lit' category.

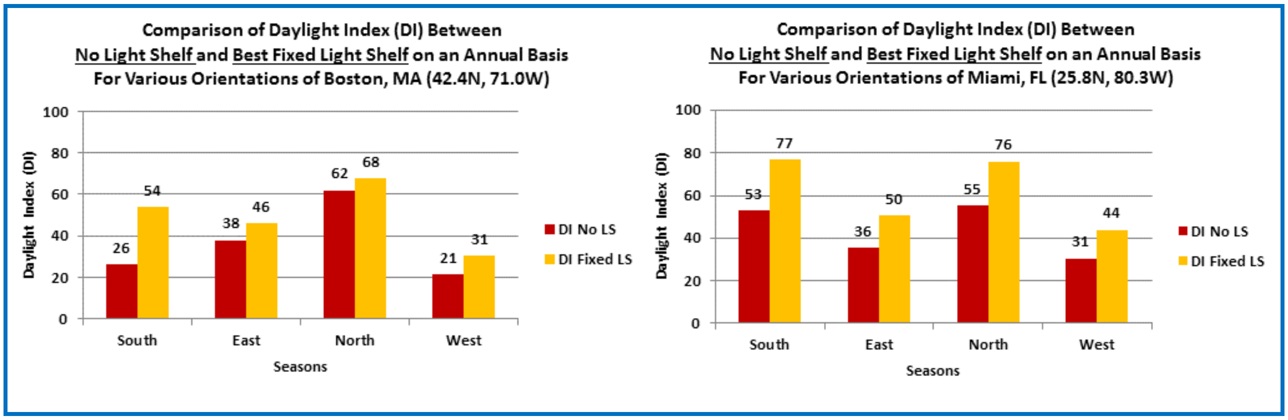


Fig. 67 Light shelf in Boston, MA and Miami, FL: 'no LS' versus 'optimized fixed LS'.

Improvement due to Adjustable Light Shelves over Fixed Light Shelves

The premise of this research was to prove/disprove the hypothesis that manual adjustability of a light shelf improves indoor daylight levels significantly enough to warrant the development and application of such a system. This was done by simulating the performance of various light shelf configurations for all four seasons and comparing them to the performance of the optimized fixed light shelf, achieved *for the same seasonal time-period*.

This research focuses on 'manually adjustable light shelves'. Keeping the practicality of manual adjustment in mind, the research assumed that the light shelf will be adjusted only four times a year, once in the middle of the four seasons of winter, spring, summer and fall. Thus, the four configuration seasons were defined such that the solstices and the equinox fell at the middle of these time periods (Fig. 68). The ranges of dates for these seasons came out to be:

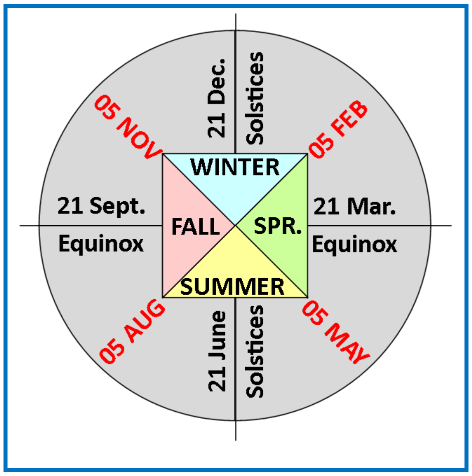


Fig. 68 The definition of the 4-seasons for this research.

- Winter: November 06 to February 05
- Spring: February 06 to May 05
- Summer: May 06 to August 05 and
- Fall: August 06 to November 05

To illustrate how the performance of the fixed light shelf was used as a base-case to assess the effectiveness of seasonally adjustable light shelves let us take the case of R0-H6-D8. This is the light shelf configuration found to be the optimal solution as an annually fixed light shelf for the south orientation of Blacksburg, VA. To find the best adjustable light shelf for say, winter season in Blacksburg, the performance of the fixed light shelf R0-H6-D8, achieved during the winter period, was used as a base-case.

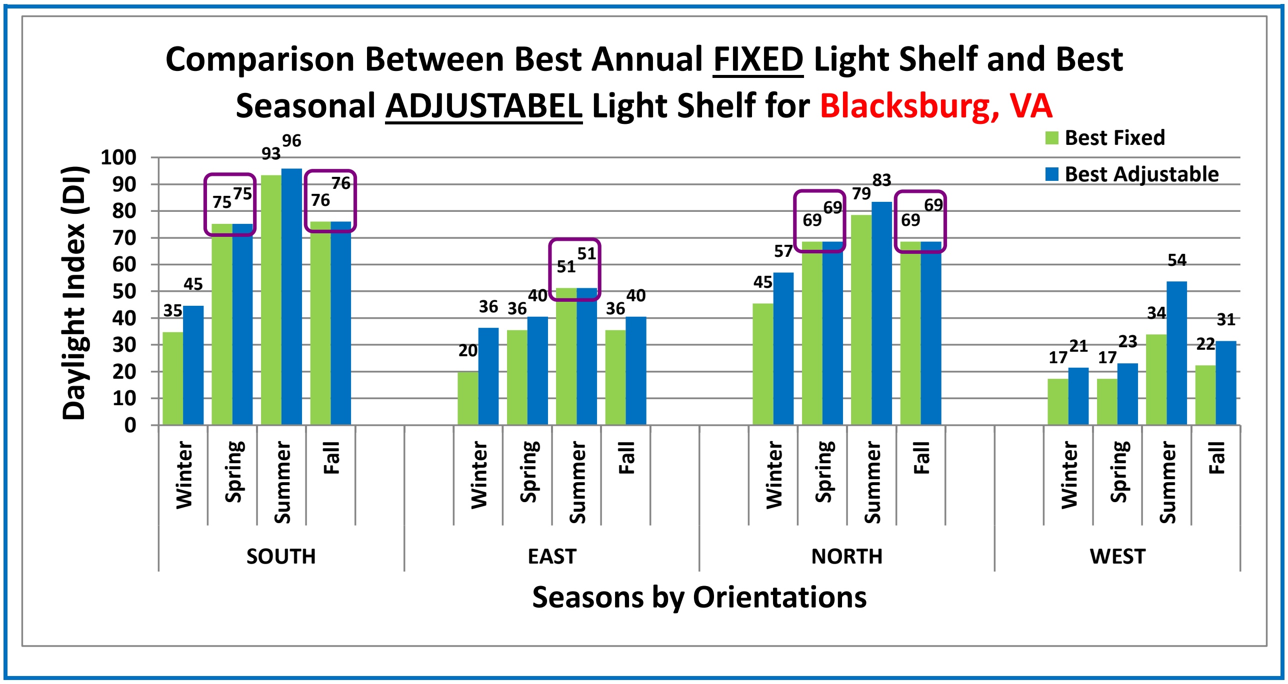


Fig. 69 Comparison of fixed LS and adjustable LS for Winter & Spring, Blacksburg, VA

The comparison of seasonally adjustable light shelves and fixed light shelves for the four cardinal directions in all four seasons for Blacksburg, VA are shown in Fig. 69. It can be observed that adjustability of a light shelf improves its performance, as compared to an optimally fixed one, for most orientations and seasons. The spring and fall of north and south orientations and the summer for the east orientation are the exceptions to this phenomenon.

Orientation and Light Shelf Performance

Openings in buildings can happen in any orientation. This research has, therefore, investigated the effect of orientation on light shelf performance by studying light shelves in the four cardinal directions (south, east, north and west) (Fig. 70). The best performing adjustable light shelves in each orientation was compared with the optimum fixed light shelf for that orientation to assess performance. From Fig. 69 one can get a good sense of the effect of orientation on light shelf performance in relation to seasons. It is observed that maximum daylight is available in the south and north orientations. In the case of the south this is what is to be expected for the northern hemisphere. However, the abundance of light in the north direction seems counter intuitive until one realizes that these graphs only show the 'well-lit' component of the total daylight penetration. North light has been traditionally preferred by painters for their art studios because of the availability of a uniform level of good daylight for most of the day from that direction.

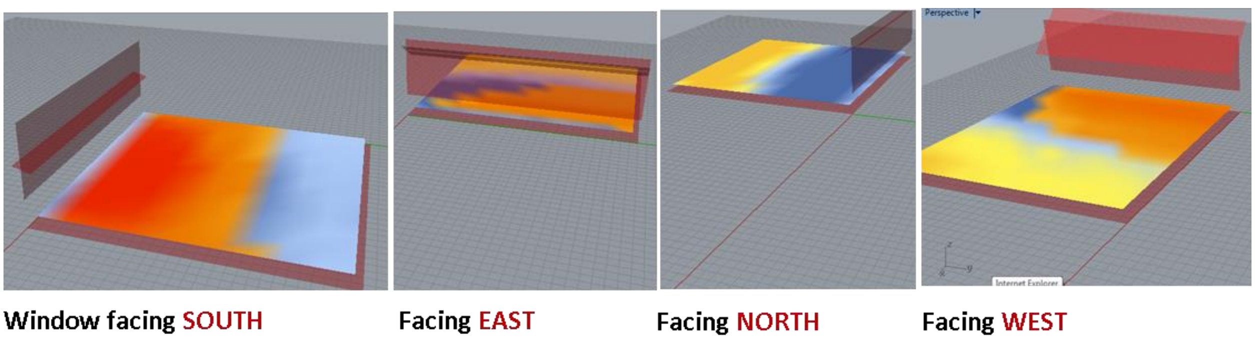


Fig. 70 Effect of orientation on light shelf performance

Effect of Latitude on Light Shelf Performance

Light shelf performance is greatly dependent on the intensity of direct sunlight at a location. Thus, this research took three distinctly different locations, Miami, FL (26°N), Blacksburg, VA (37°N), and Boston, MA (42°N) to study the effect of a change of latitude on light shelf performance (Fig. 71). The method of investigation described for Blacksburg, VA in the earlier sections was repeated for these additional locations of Miami and Boston and the results assessed to evaluate the effect of latitude on light shelf performance in regards to seasonally adjustable light shelves.

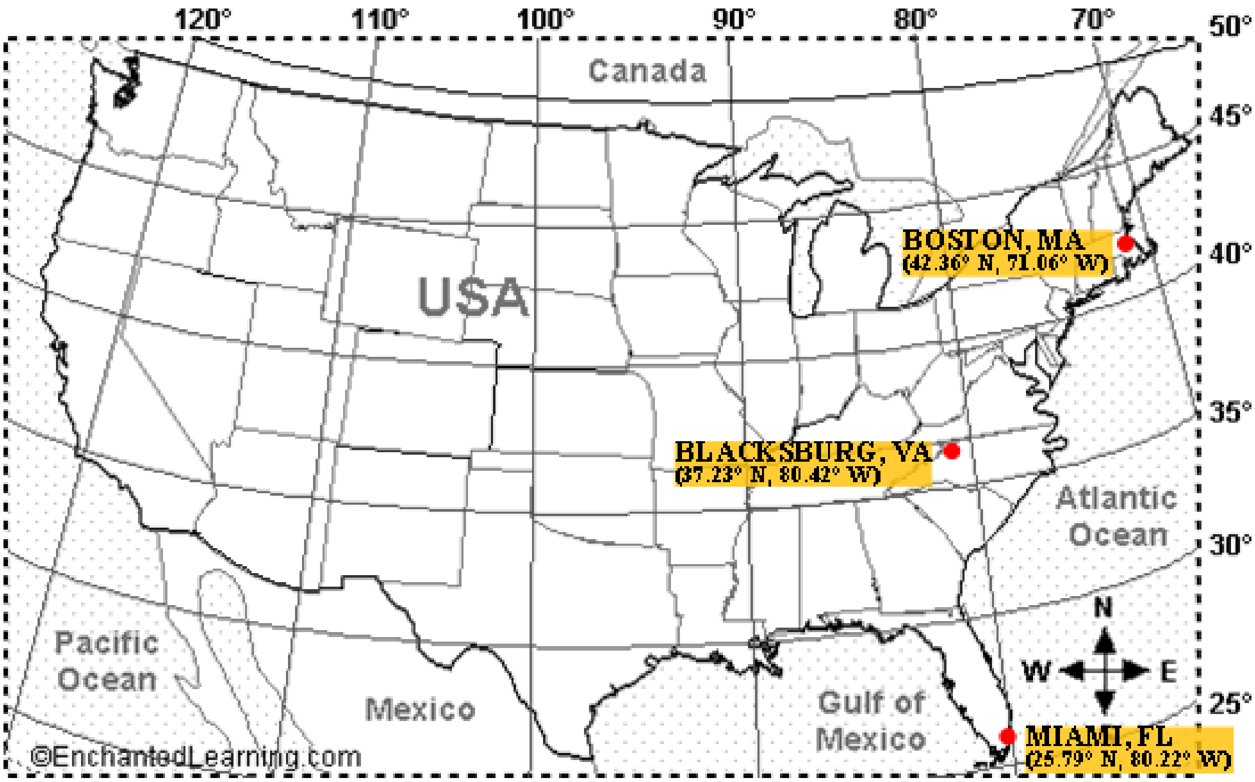


Fig. 71 Three cities for study of the effect of Latitude on light shelf performance (https://dr282zn36sxxg.cloudfront.net/datastreams/f-d%3A59d3979c661422c7966dfd67bb26f4a8b742dc23197e40dbe984078c%2BIMAGE%2BIMAGE.1) [Accessed 17-April-2014]. Used under fair use 2014.

This study showed that performance improvement from adjustable light shelves compared to fixed ones varied by the latitude of the place as well as the orientation of the opening in that location. For example, for openings facing the south, the greatest improvement in performance due to an adjustable light shelf as compared to an optimum fixed one happened for Miami in the summer (Fig. 72a). The next in line in terms of improvement happened for Blacksburg, also in summer. For spring and fall, adjustable light shelf did not show any improvement over optimized fixed ones in any of the three cities under study. For a south facing opening in Boston an adjustable light shelf showed no improvement over an optimized fixed one during any of the four seasons. In general, adjustable light shelves, when compared with optimized fixed ones, performed better for lower latitudes that higher ones. There were exceptions to this. For example, for a west oriented opening, adjustable light shelves were most effective for mid-latitude such as Blacksburg (Fig. 72d).

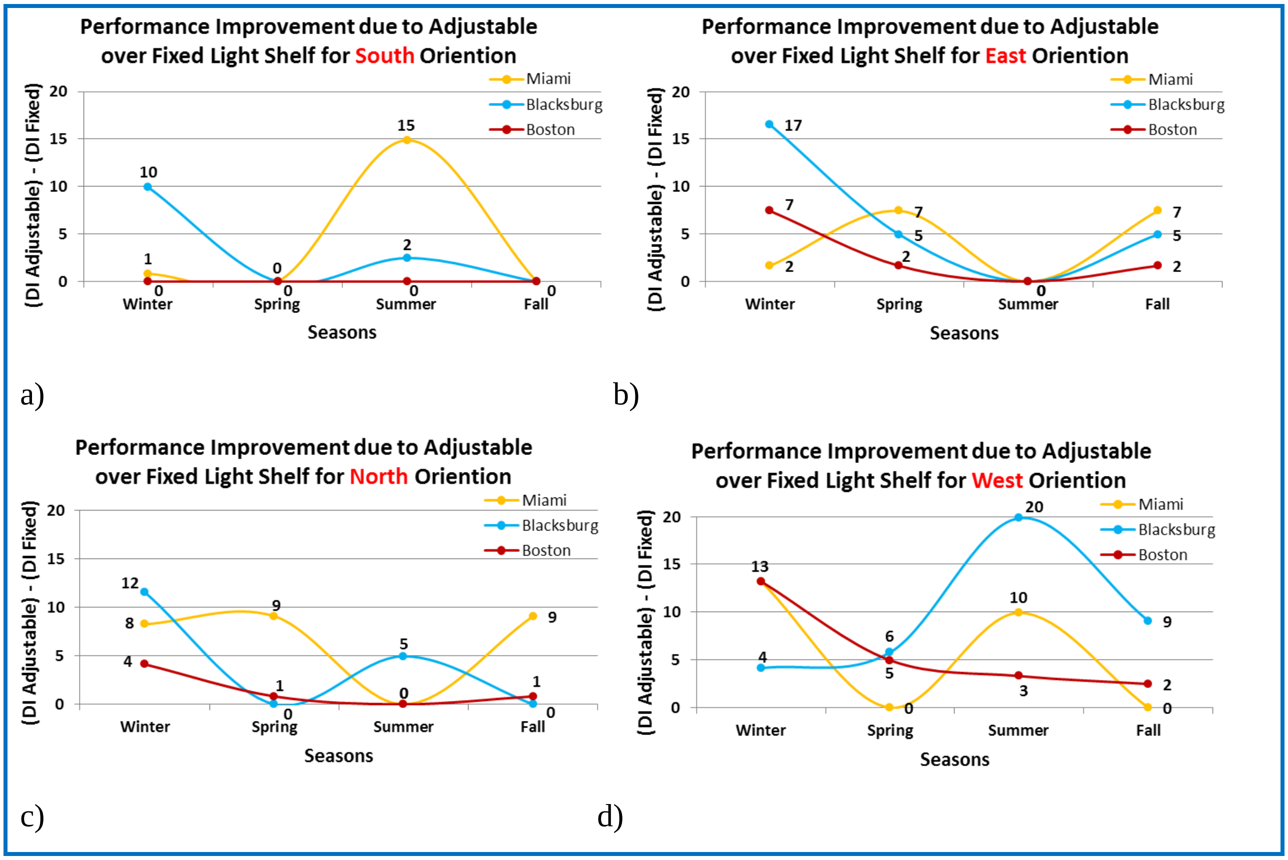


Fig. 72 Correlation between light shelf performance and latitude.

Some of the observations from this set of graphs can be summarized as follows:

- South: Miami showed good performance for summer while Blacksburg did well in the winter. For Boston, an adjustable light shelf did not show improved performance in any of the seasons.
- East: All three cities showed improved performance with adjustable light shelves in all seasons except in the summer.
- North: Blacksburg and Miami showed benefit from adjustable light shelves in winter. Miami showed good performance in the spring and fall as well while Blacksburg showed benefit in the summer. Boston's benefit from adjustable light shelf was minimal for most seasons in this orientation.
- West: except for Miami in spring and fall all three cities showed benefit from adjustable light shelf in all seasons, the summer and the winter months faring prominently.

Segmented Adjustable Light Shelf and Simple Adjustable Ones

A limited number of tests were done with light shelves that are in two segments – an exterior and an interior part where the two could be adjusted independently (Fig. 73). Light shelves of this nature are termed 'segmented' while ones in one-piece are called 'simple' in this document. Variables used in the study of segmented light shelves were:

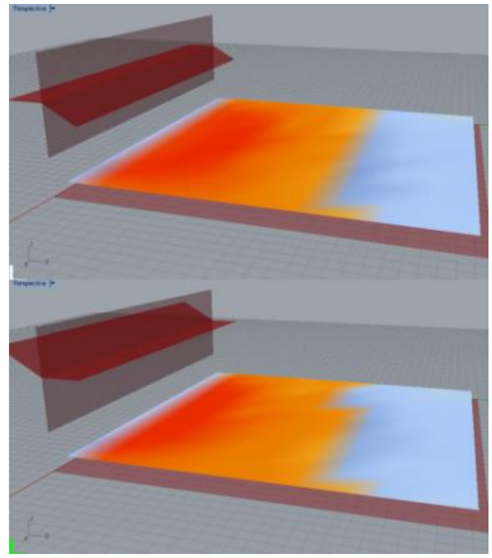
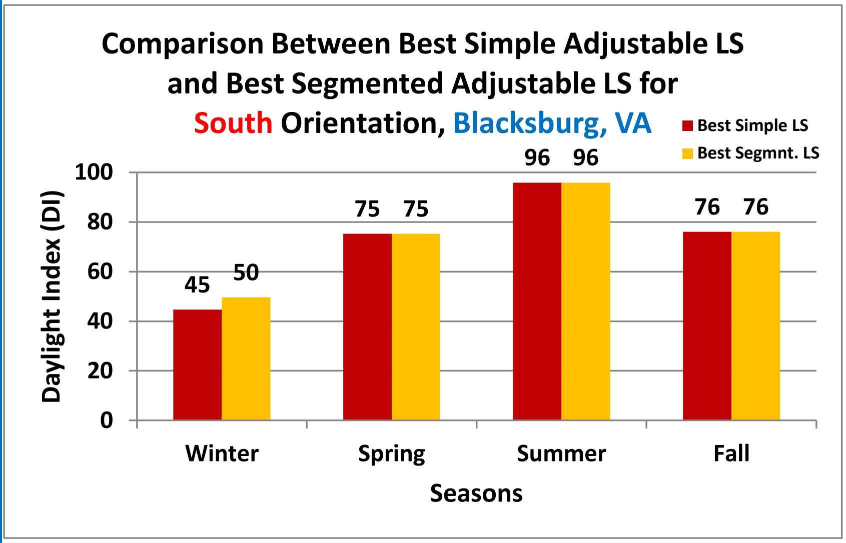


Fig. 73 2-Piece Light Shelf

- RP (rotation LS outside) = 0, 15, 30 & 45 deg.
- RS (rotation LS inside) = 0, 15, 30 & 45 degrees
- DP (depth of LS outside) = 1, 2, 3 & 4 feet.
- DS (depth of LS inside) = 1, 2, 3 & 4 feet.
- H (height of the mid-point of the LS = 6, 7, 8 & 9 feet.

This generated a total of 1024 combinations (4RPx4RSx4DPx4DSx4H) of light shelves for each of the seasons. On a laptop with a 2.5 GHz CPU (Intel i5 2520M), for the four seasons, the run took 9-days and 14 hours to complete this simulation. The best simple adjustable light shelf for each season was used as the base case for comparison. As seen in Fig. 74, for the south orientation of Blacksburg, VA, only in winter did the segmented light shelf show an improvement of performance over its simple counterpart. The reason becomes clear when one compares the light shelf configurations between the two groups (Fig. 74, right). Except for winter, the added flexibility of the segmented light shelf to vary the settings of its inner and outer parts independently led essentially to the same light shelf configuration as the non-segmented one. Light shelf performance in this research is being assessed with the amount of .well-lit area achieved in the interior space. It is possible that this measure is being affected more by the shading characteristic of the light shelf (the amount of direct sunlight it is obstructing) as opposed to the light reflective ability if its surface. As a result, in case of both the simple light shelf and the segmented one, the same geometry is creating the most shading effect. Thus, in reporting the best performing light shelf, the simulation program is selecting essentially the same configuration in case of both the simple and the segmented light shelf.

As with Blacksburg, in Miami and Boston as well, we see that the use of segmented light shelves, where the inner and the outer sections could be adjust independently, did not improve performance except slightly in winter (Fig. 75 and Fig. 76).

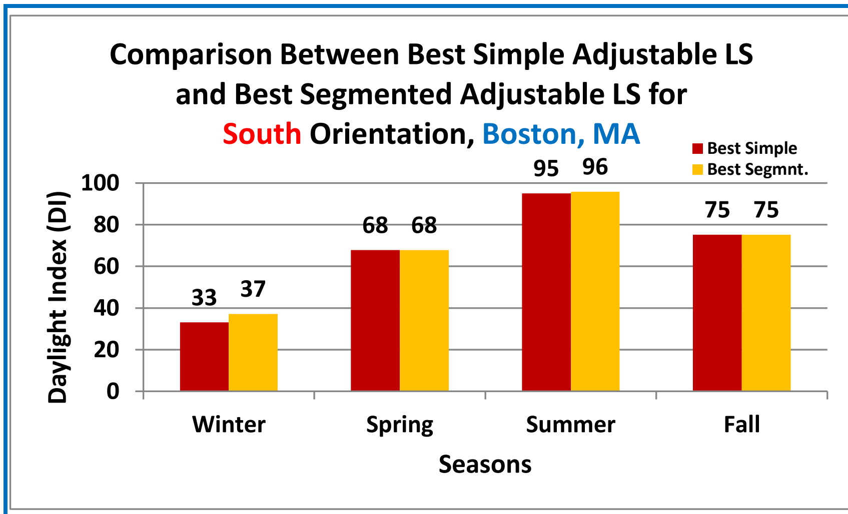


Best Simple Adjustable and Best Segmented Adj. for Blacksburg

	Best Simple	Best Segmnt.
Winter	45	50
Spring	75	75
Summer	96	96
Fall	76	76

For South Orientation, Blagasburg, VA		
	Best Simple	Best Segmnt.
Winter	R15-H9-D8	RP15-RS15-DP3-DS4-H9
Spring	R0-H6-D8	RP0-RS0-DP4-DS4-H6
Summer	R0-H6-D6	RP0-RS0-DP3-DS3-H6
Fall	R0-H6-D8	RP0-RS0-DP4-DS4-H6

Fig. 74 Comparison of simple and segmented light shelf for south orientation, Blacksburg

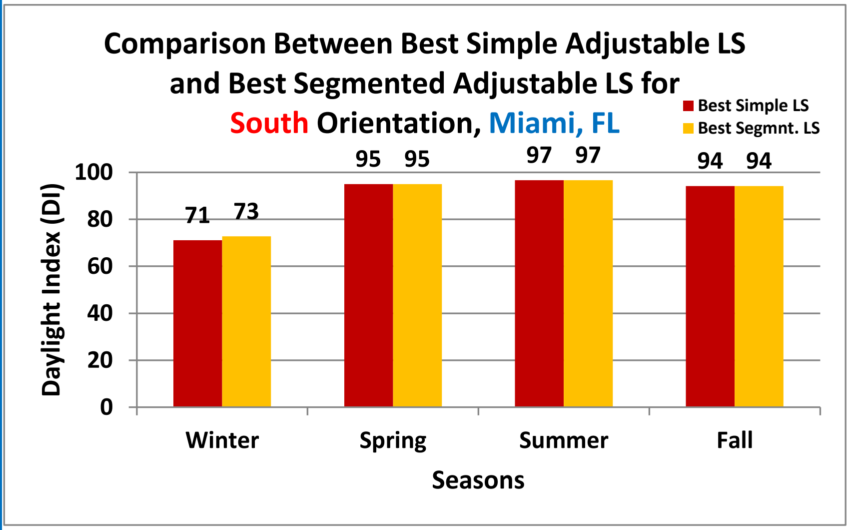


Best Simple Adjustable and Best Segmented Adj. for Boston

	Best Simple	Best Segmnt.
Winter	33	37
Spring	68	68
Summer	95	96
Fall	75	75

For South Orientation, Boston, MA		
	Best Simple	Best Segmnt.
Winter	R0-H6-D8	RP15-RS0-DP1-DS3-H9
Spring	R0-H6-D8	RP0-RS0-DP4-DS4-H6
Summer	R0-H6-D8	RP15-RS0-DP4-DS4-H6
Fall	R0-H6-D8	RP0-RS0-DP4-DS4-H6

Fig. 75 Comparison of simple and segmented light shelf for south orientation, Blacksburg



Best Simple Adjustable and
Best Compound Adj. for Miami, FL

	Best Simple	Best Segmnt.
Winter	71	73
Spring	95	95
Summer	97	97
Fall	94	94

For South Orientation, Miami, FL

	Best Simple	Best Segmnt.
Winter	R0-H7-D8	RP15-RS0-DP4-DS4-H8
Spring	R0-H6-D8	RP0-RS0-DP4-DS4-H6
Summer	R15-H6-D8	RP15-RS15-DP4-DS4-H6
Fall	R0-H6-D8	RP0-RS0-DP3-DS4-H6

Fig. 76 Comparison of simple and segmented light shelf for south orientation, Blacksburg

The Relative Effect of Different Variables on Light Shelf Performance

To understand which light shelf parameter had the greatest effect on performance the best light shelf configurations for each season were re-evaluated. The respective variable whose effect was to be studied was varied keeping all other variables constant. For example, R15-H9-D8 was found to be the best performing light shelf for winter in Blacksburg, VA. To study the effect of rotation 'R', in this case, was varied through 0, 15, 30 and 45 degrees while 'H' and 'D' were kept constant at '9' and '8' respectively (Fig. 77). We see that for winter, the variation of 'rotation' has the most significant effect with a clear 'peak' at 15-degrees while the change of 'height' and 'depth' (Fig. 77, bottom) keeps the range of the well-lit zone (yellow) fairly constant, indicating a minimal effect on performance with change in these variables.

A set of charts like the ones in Fig. 77 can be generated for different light shelf variables, seasons, orientations and location (Fig. 78). They can give a manufacturer or user of light shelves an immediate visual clue regarding the potential of different light shelf combinations to harvest daylight of various categories (under-lit, well-lit and over-lit). The graphs will also indicate if there is a possibility of an increase in daylighting performance if one or more of the variables are made adjustable. Thus, with a set of charts of this nature one can make an informed decision, without resorting to detailed calculations, about appropriate light shelf design for that instance. Charts like these can, therefore, be an initial guide to manufacturers or users of light shelves in their assessment of light shelf viability for any given context.

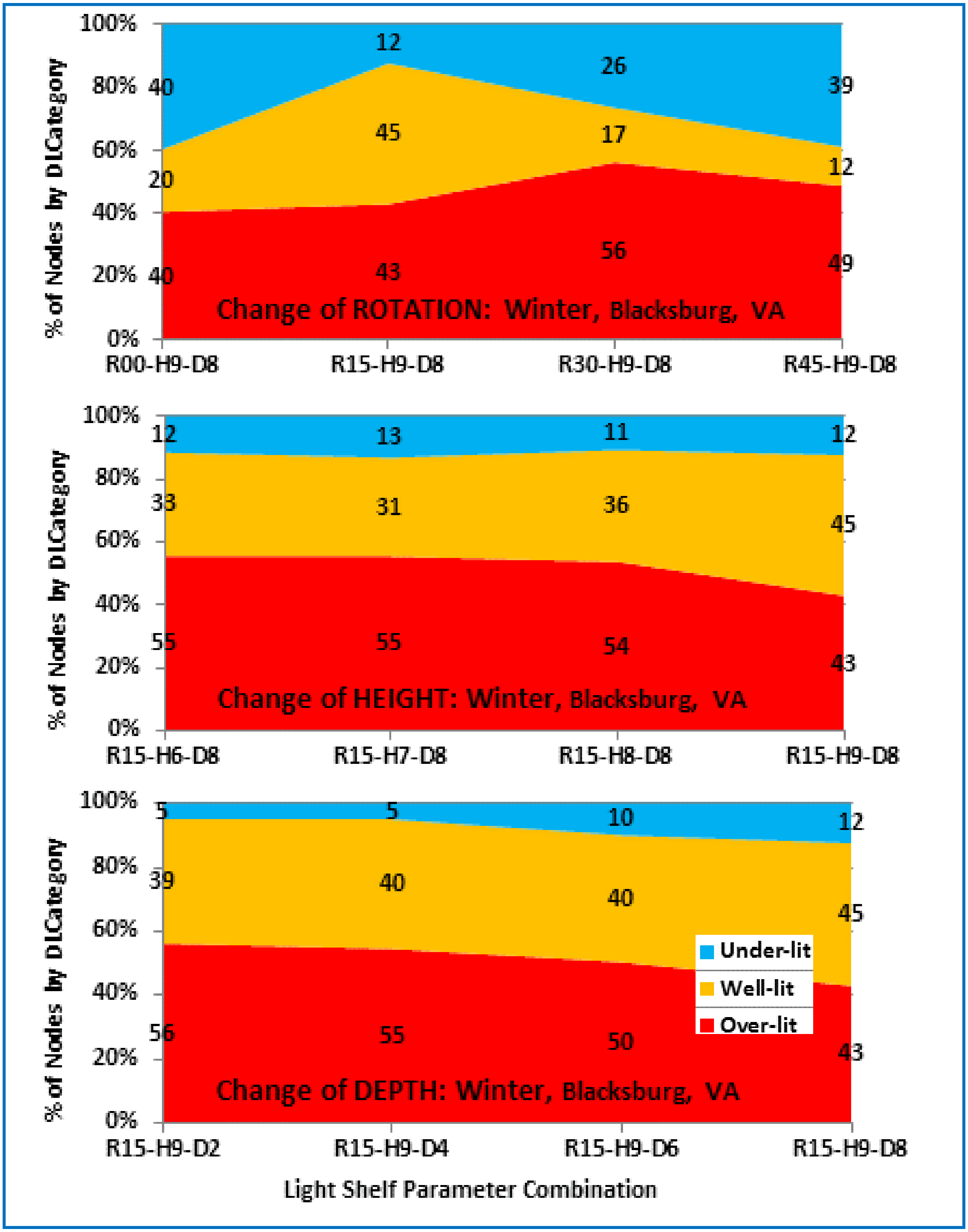


Fig. 77 Relative effect of Rotation, Height and Depth on light shelf performance

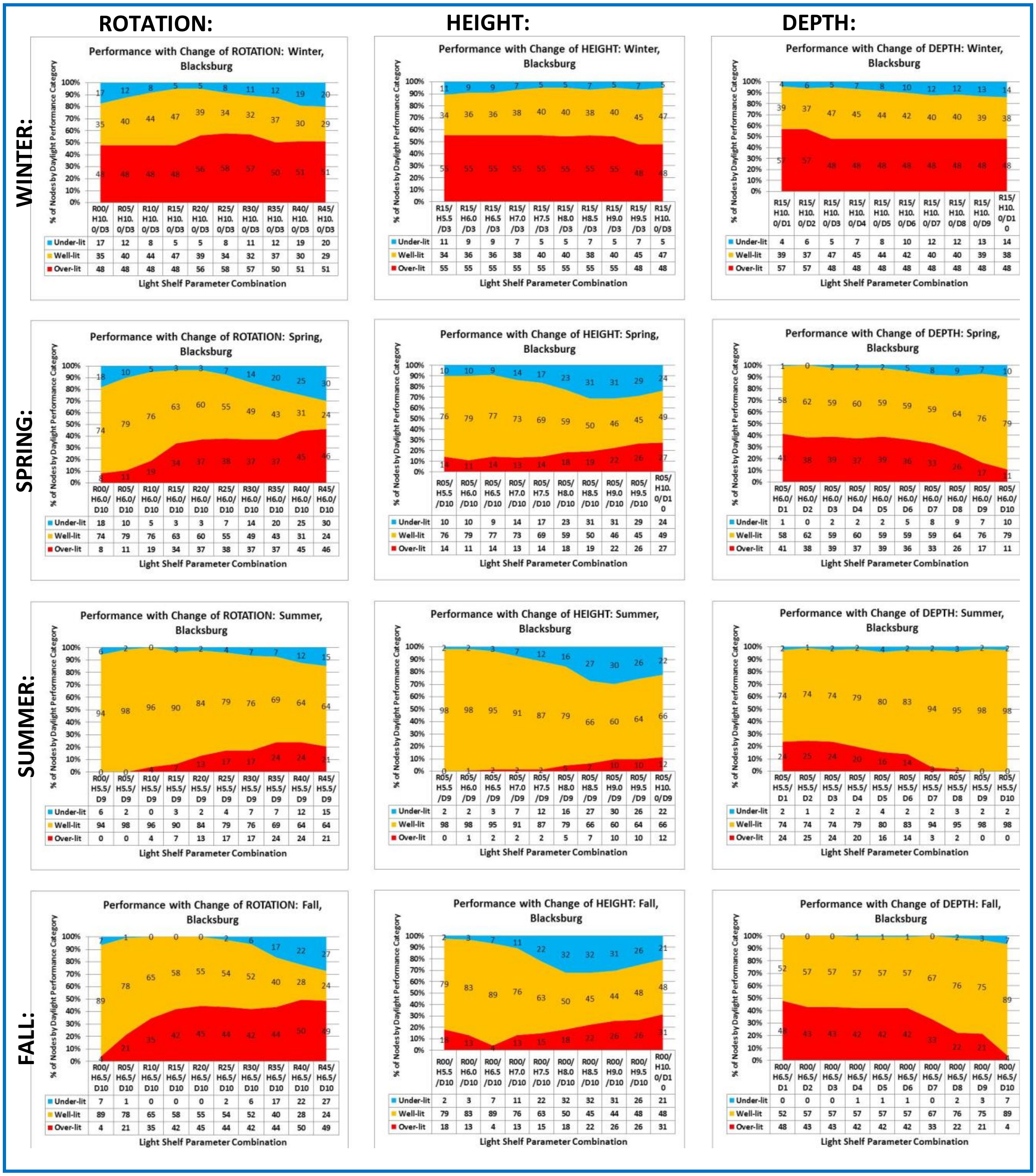


Fig. 78 Graph showing relative effect of change of parameters over seasons

The effect of granularity of the variables on performance

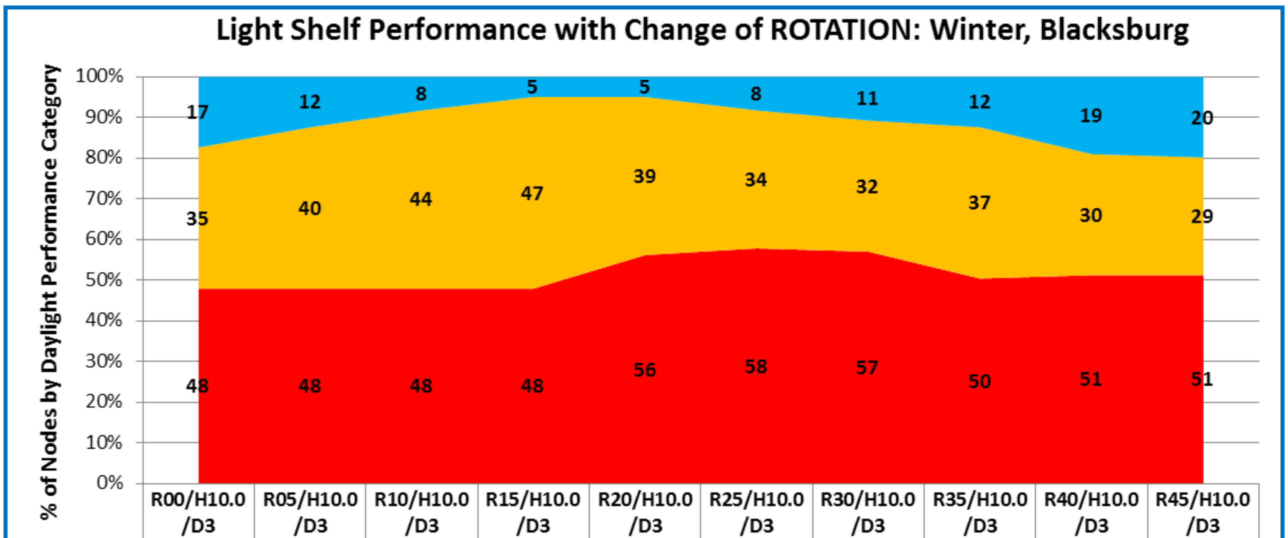
To find out how the granularity of the variables affected light shelf performance, simulations were re-run with finer increment in the variable range. For example 'rotation' now had 5° increments compared to the 15° previously. The new range of variables for all three light shelf parameters is shown in Fig. 79:

Rotation (degree)	0	5	10	15	20	25	30	35	40	45
Height (ft)	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
Depth (ft)	1	2	3	4	5	6	7	8	9	10

10-STEPS: Total Combinations: 10 x 10 x 10 = 1000

Fig. 79 Variable values for 10-step increment in each of the three light shelf adjustability.

Results from this series of simulations did show greater details but corroborated what was found earlier. For example, Fig. 80 is a 10-step version of Fig. 77, top, which had only 4-data points each. Here the total range of rotation, 0 – 45 degrees, was divided into 10-segments. The results showed greater detail in the correlation between rotation and light shelf performance but maintain the same general trend.



	R00/H10.0/D3	R05/H10.0/D3	R10/H10.0/D3	R15/H10.0/D3	R20/H10.0/D3	R25/H10.0/D3	R30/H10.0/D3	R35/H10.0/D3	R40/H10.0/D3	R45/H10.0/D3
Under-lit	17	12	8	5	5	8	11	12	19	20
Well-lit	35	40	44	47	39	34	32	37	30	29
Over-lit	48	48	48	48	56	58	57	50	51	51

Fig. 80 Increased granularity of variables improved details in the graph.

4.3.2 Validation of Results

4.3.2.1 Validation Using Experimental Studies

The experimental methodology that has been tried at the beginning of this research proved to be inadequate to investigate the large number of variables and their combinations called for in this research. However, for narrow time slots, when the natural sky conditions and the research parameters corroborated well we see good correspondence between experimental and simulation results.

Experimental validation methodology

The initial focus of the experimental studies in this research was to develop a testing methodology that could produce repeatability of results. Towards this goal, the daylight levels inside a scale model were recorded at specific altitude angle of the sun such as 0, 30, 45 and 60 degrees. Similarly, the azimuth angle of the sun was always kept at 180-degree east of north. Using the altitude and azimuth angles used for a particular experiment the corresponding time and date of the year that experiment represented was found (Fig. 81). This conversion was necessary to allow comparison of experimental results with those from simulation, where the illumination results were identified with time and date.

Astronomical Applications Dept.
U.S. Naval Observatory
Washington, DC 20392-5420
BLACKSBURG, VIRGINIA
W 80 25, N37 14
Altitude and Azimuth of the Sun

08 April, 2014 (EST)

	Altitude	Azimuth (E or N)
h:m	degree	degree
13:20	60.1	178.3
13:21	60.1	178.8
13:22	60.1	179.3
13:23	60.1	179.8
13:24	60.1	180.3
13:25	60.1	180.8
13:26	60.1	181.3
13:27	60.1	181.8
13:28	60.1	182.3
13:29	60.1	182.8
13:30	60.1	183.3

28 February, 2014 (EST)

	Altitude	Azimuth (E or N)
h:m	degree	degree
12:30	45	178.6
12:31	45	178.9
12:32	45	179.3
12:33	45	179.6
12:34	45	180
12:35	45	180.3
12:36	45	180.7
12:37	45	181
12:38	45	181.4
12:39	45	181.7
12:40	45	182.1

Source: http://aa.usno.navy.mil/data/docs/AltAz.php
Retreved: 02 March, 2014

Fig. 81 Date and time of experiments derived from sun angles. Used under fair use 2014

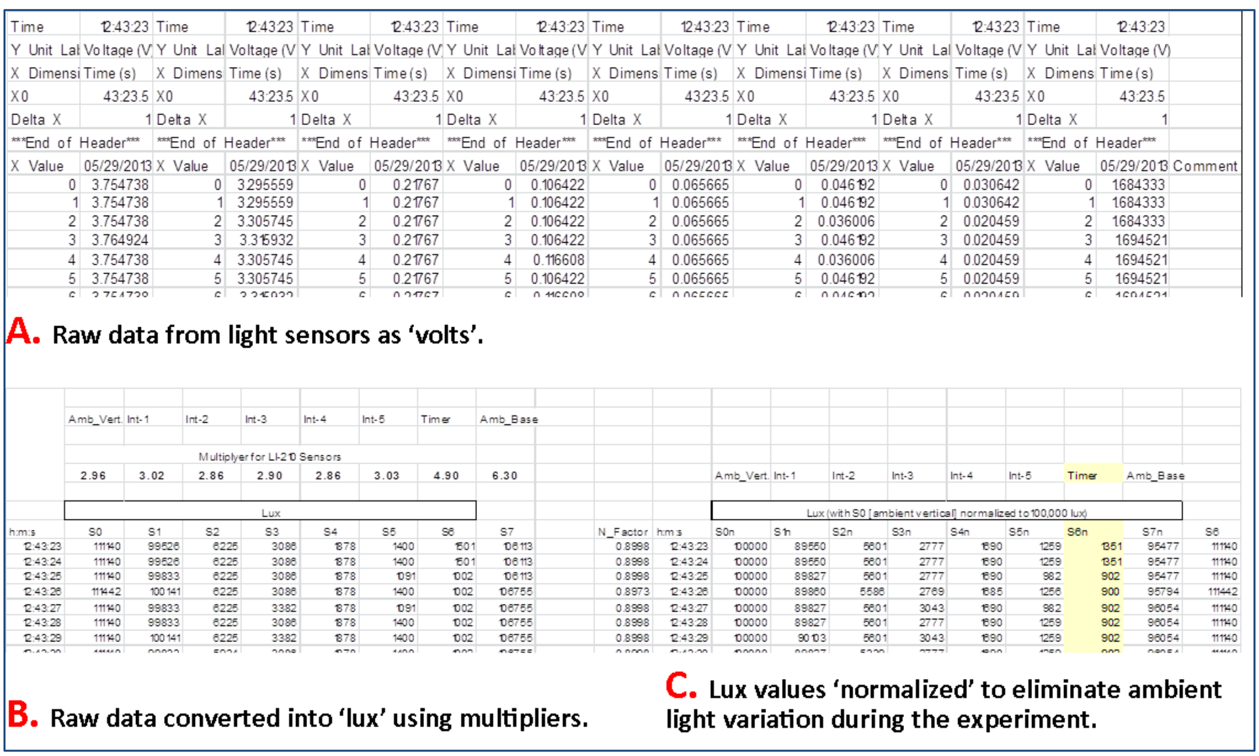
Next a set of experiments were identified which were carried out in a narrow band of time under a fairly clear sky condition.

Experiment date: 29 May, 2013; Sun altitude: 60-degrees; Sun Azimuth: 180-degrees, East of North.
Corresponds to: 01:24 pm, 08 April, 2014 in Blacksburg, VA

Sky condition at the time of the above experiments

Fig. 82 Experiment used for validation.

The illumination data derived from the above experiment was subsequently post-processed to make it comparable to simulation data (Fig. 83).



Time	12:43:23	Time	12:43:23	Time	12:43:23	Time	12:43:23	Time	12:43:23	Time	12:43:23	Time	12:43:23	Time	12:43:23	
Y Unit Lal	Voltage (V	Y Unit Lal	Voltage (V	Y Unit Lal	Voltage (V	Y Unit Lal	Voltage (V	Y Unit Lal	Voltage (V	Y Unit Lal	Voltage (V	Y Unit Lal	Voltage (V	Y Unit Lal	Voltage (V)	
X Dimensi	Time (s)	X Dimens	Time (s)	X Dimens	Time (s)	X Dimensi	Time (s)	X Dimens	Time (s)	X Dimensi	Time (s)	X Dimens	Time (s)	X Dimens	Time (s)	
X0	43:23.5	X0	43:23.5	X0	43:23.5	X0	43:23.5	X0	43:23.5	X0	43:23.5	X0	43:23.5	X0	43:23.5	
Delta X	1	Delta X	1	Delta X	1	Delta X	1	Delta X	1	Delta X	1	Delta X	1	Delta X	1	
End of Header		***End of Header***		***End of Header***		***End of Header***		***End of Header***		***End of Header***		***End of Header***		***End of Header***		
X Value	05/29/2013	X Value	05/29/2013	X Value	05/29/2013	X Value	05/29/2013	X Value	05/29/2013	X Value	05/29/2013	X Value	05/29/2013	X Value	05/29/2013	Comment
0	3.754738	0	3.295559	0	0.21767	0	0.106422	0	0.065665	0	0.046192	0	0.030642	0	1684333	
1	3.754738	1	3.295559	1	0.21767	1	0.106422	1	0.065665	1	0.046192	1	0.030642	1	1684333	
2	3.754738	2	3.305745	2	0.21767	2	0.106422	2	0.065665	2	0.036006	2	0.020459	2	1684333	
3	3.764924	3	3.315932	3	0.21767	3	0.106422	3	0.065665	3	0.046192	3	0.020459	3	1694521	
4	3.754738	4	3.305745	4	0.21767	4	0.116608	4	0.065665	4	0.036006	4	0.020459	4	1694521	
5	3.754738	5	3.305745	5	0.21767	5	0.106422	5	0.065665	5	0.046192	5	0.020459	5	1694521	

A. Raw data from light sensors as ‘volts’.

	Amb_Vert.	Int-1	Int-2	Int-3	Int-4	Int-5	Timer	Amb_Base
	Multiplyer for LI-210 Sensors							
	2.96	3.02	2.86	2.90	2.86	3.03	4.90	6.30
	Lux							
h:m:s	S0	S1	S2	S3	S4	S5	S6	S7
12:43:23	111140	99526	6225	3086	1878	1400	1501	106113
12:43:24	111140	99526	6225	3086	1878	1400	1501	106113
12:43:25	111140	99833	6225	3086	1878	1091	1002	106113
12:43:26	111442	100141	6225	3086	1878	1400	1002	106755
12:43:27	111140	99833	6225	3382	1878	1091	1002	106755
12:43:28	111140	99833	6225	3086	1878	1400	1002	106755
12:43:29	111140	100141	6225	3382	1878	1400	1002	106755

B. Raw data converted into ‘lux’ using multipliers.

		Amb_Vert.	Int-1	Int-2	Int-3	Int-4	Int-5	Timer	Amb_Base	
		Lux (with S0 [ambient vertical] normalized to 100,000 lux)								
N_Factor	h:m:s	S0n	S1n	S2n	S3n	S4n	S5n	S6n	S7n	S6
0.8998	12:43:23	100000	89550	5601	2777	1690	1259	1351	95477	111140
0.8998	12:43:24	100000	89550	5601	2777	1690	1259	1351	95477	111140
0.8998	12:43:25	100000	89827	5601	2777	1690	982	902	95477	111140
0.8973	12:43:26	100000	89860	5586	2769	1685	1256	900	95794	111442
0.8998	12:43:27	100000	89827	5601	3043	1690	982	902	96054	111140
0.8998	12:43:28	100000	89827	5601	2777	1690	1259	902	96054	111140
0.8998	12:43:29	100000	90103	5601	3043	1690	1259	902	96054	111140

C. Lux values ‘normalized’ to eliminate ambient light variation during the experiment.

Fig. 83 Post-processing of raw data from validation experiment.

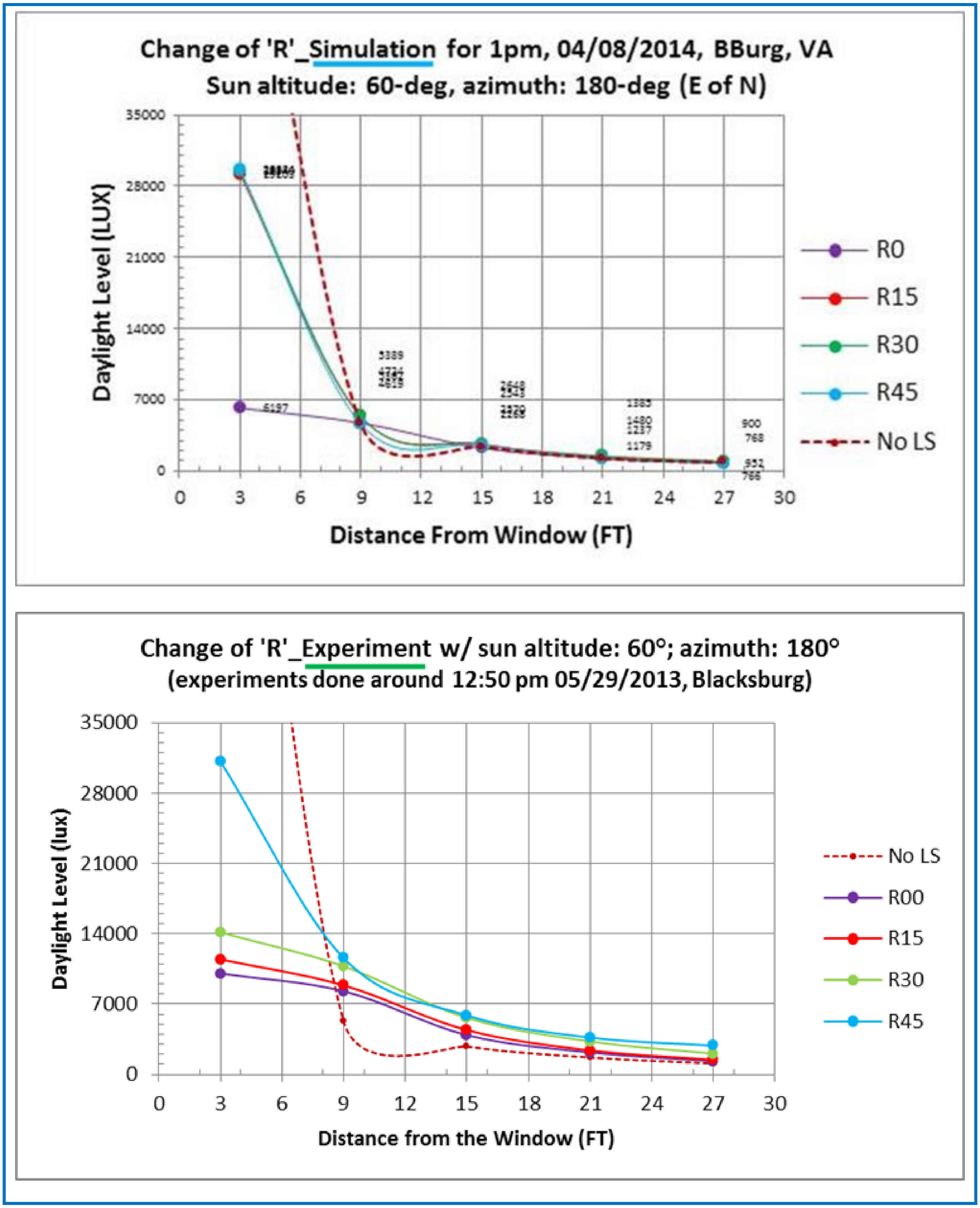


Fig. 84 Simulation results show good correspondence with experimental results.

Limitation of the experimental validation methodology

The experimental validation approach used in this study was found not to work when the model base was excessively rotated towards the ground or the sky (as in 0 or 30 degree images in Fig. 41). A possible reason for this may be the unrealistically large exposure of the light sensors to ground or the sky in such instances, causing the illumination readings to deviate from the normal.

The validation procedure described above derives a date and time of an experiment from the altitude and azimuth angle used in the experiment. When this was done for a sun angle that translated into a winter date (28^{th} February, 2014 for Blacksburg, VA) there was again a disagreement between the experimental and simulation results. This is probably because the simulation calculations, using climate data, was accounting for a winter sky which the experiments, done in the end of May, would not match.

4.3.2.2 Validation Using Statistical Analysis

Light shelf performance results from simulation studies were analyzed using statistical technique of regression analysis. The goal of this analysis was to look for the following:

- How do rotation, height and depth influence the daylight availability numbers?
- Which of the above variables would benefit most from being made adjustable?

Procedure used in Statistical Analysis

Only data from a south facing opening in Blacksburg, VA was used for the statistical analysis. For this exercise the daylight availability (DA) matrix, i.e. the grid of numbers generated by each light shelf configuration, was first averaged to one single number. Next, multiple linear regression analysis was done with the statistical software ‘R’. Initial data used for the analysis came from a 5x5 sensor grid to minimize computation time. The regression model was run on both the actual data and coded data. The model with the coded values showed a slightly better fit but the non-coded values were more easily interpretable and thus preferred. Finally the data from the 11x11 sensor grid was used to run similar models. Results from these corroborated with those from the 5x5 grid data. A model was also run with 2^{nd} degree interactions but the results came out as mostly non-significant. As 2^{nd} degree interactions tend to make interpretation less clear, these results were not ultimately used.

Results from Statistical Analysis

Statistical Analysis found the following trend with the three basic variables

- Height had no effect on the averaged DA (Fig. 85)
- Depth had inverse relationship with DA (Fig. 85)
- Rotation has a parabolic relationship with DA, reaching the highest value around 25 degree rotation. (Fig. 86)

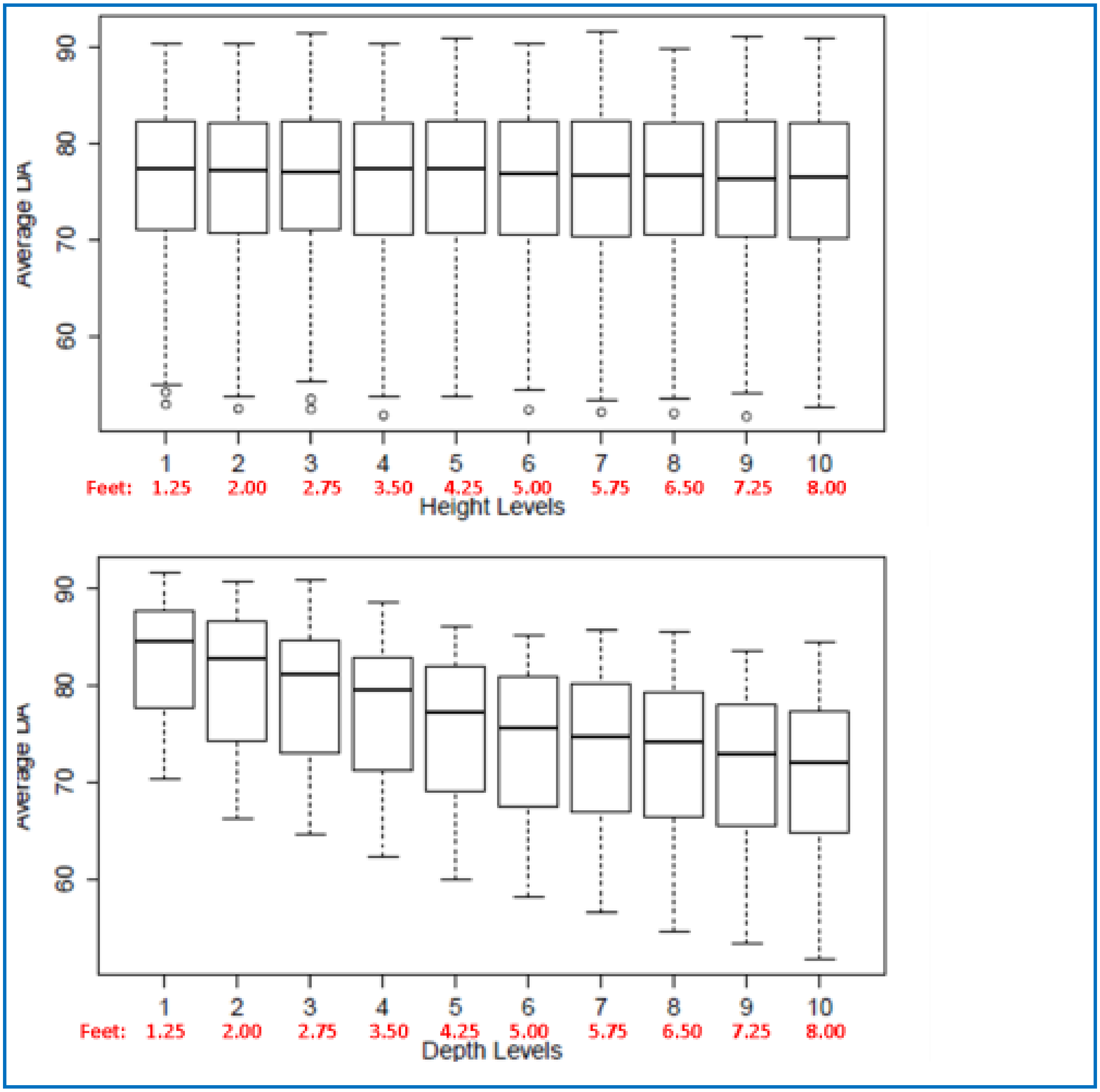


Fig. 85 Average Daylight Availability with change of Height and Depth.

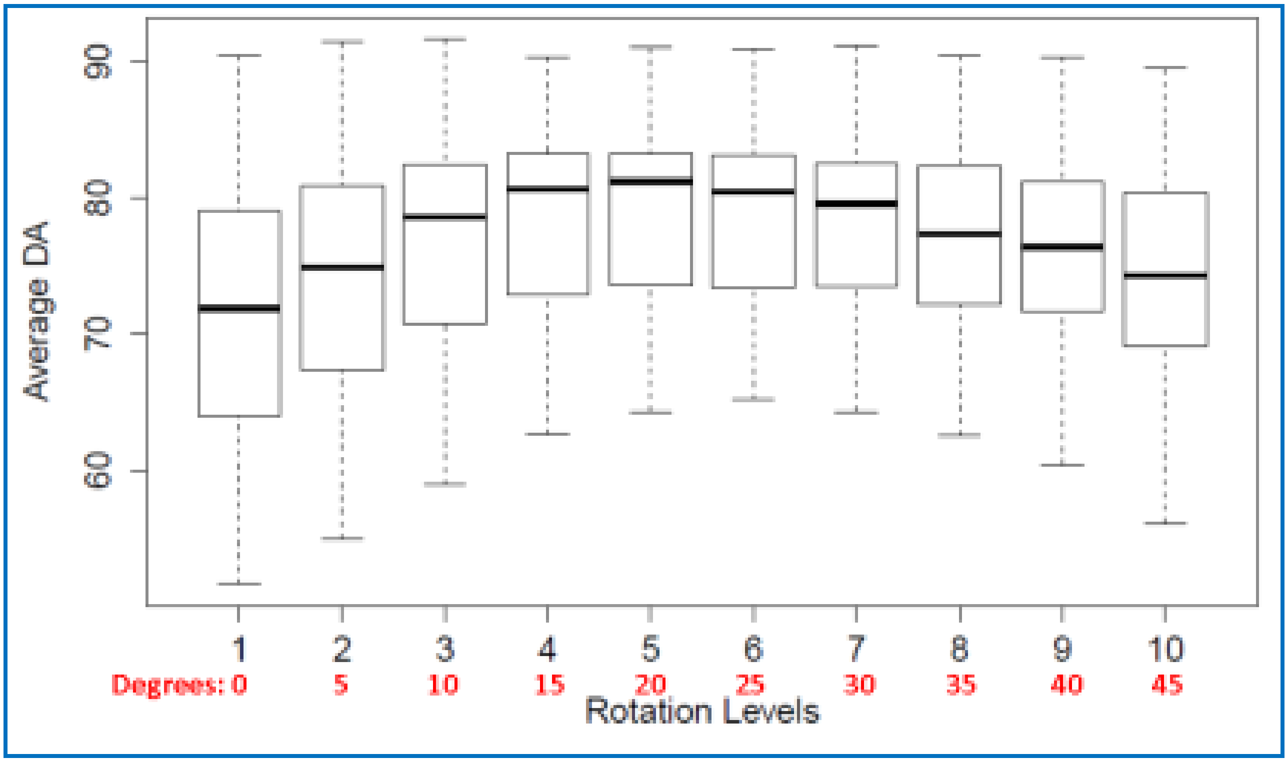


Fig. 86 Average Daylight Availability with change of Rotation

As to the second inquiry regarding which variable would benefit most from being made seasonally adjustable, the issue was studied with interaction plots. Here the variable being studied was plotted on the x-axis and the corresponding daylight performance (DA) values were plotted on the y-axis. The interaction between the x and the y axis was represented by a single line for each of the four seasons. Results from this part of the analysis can be summarized as follows:

- We saw in the last section that 'height' did not have any significant effect on daylight availability (DA). Therefore, height was not considered in this phase of the analysis.
- For the depth variable, the DA lines are fairly parallel (Fig. 87, top) indicating that although, different seasons have different average DA levels, the correlation between light shelf depth and DA values is very similar for all seasons. This shows that it would not be beneficial to change the depth of light shelves on a seasonal basis. The graph also shows that light shelf depth has an inverse relationship to daylight performance, i.e. less deep light shelves give better performance in all seasons.

- In the case of rotation, however, the daylight level peaked at different light shelf angle in different seasons (Fig. 87, bottom). This indicates that to get maximum daylight all year round, the rotation of the light shelf needs to be changed on a seasonal basis, varying between 17 and 27 degrees between the seasons.

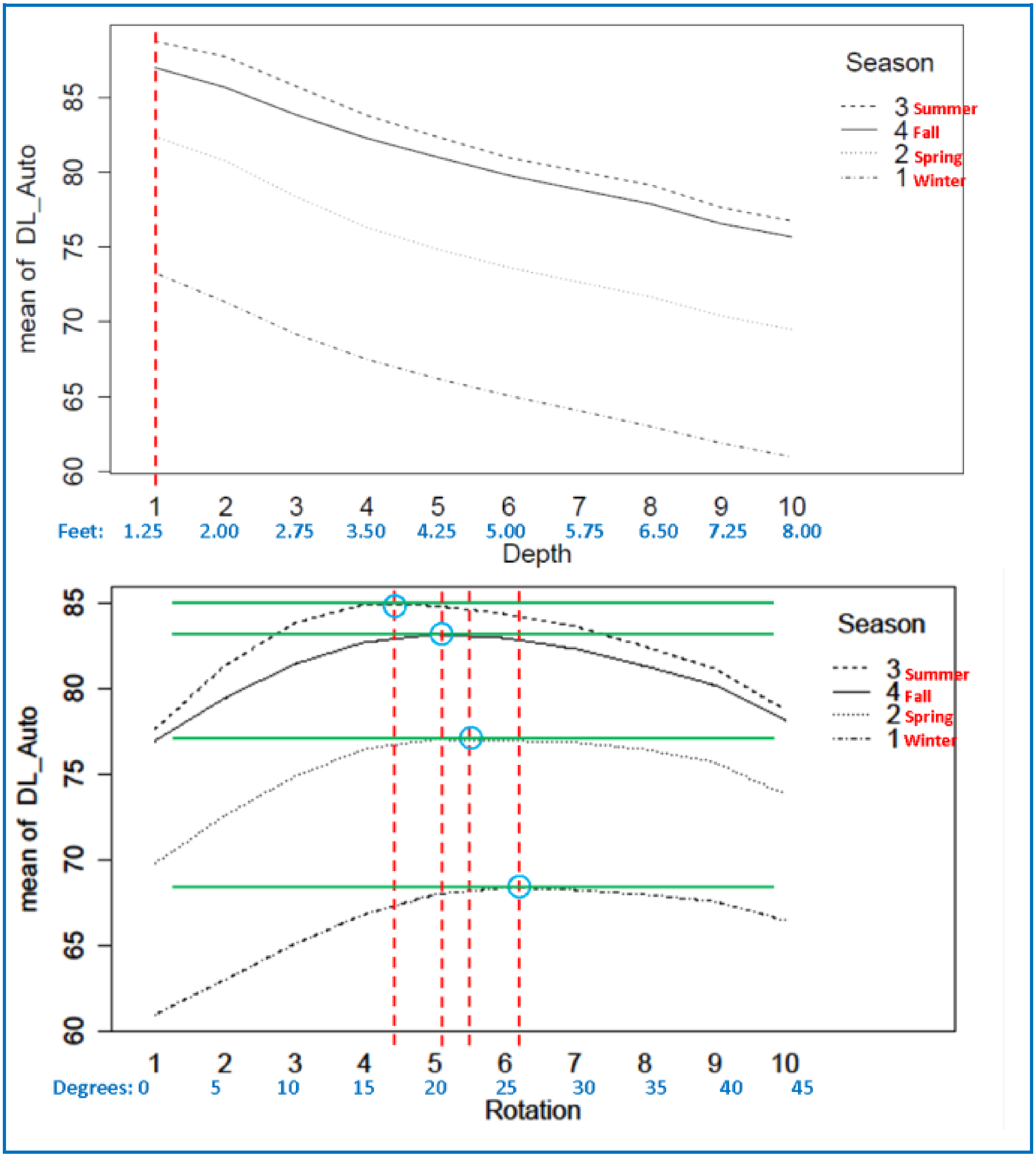


Fig. 87 Interaction plots between depth & seasons (top) and rotation & season (bottom)

Chapter 5. Conclusions and Implications

5.1 Framework Development

The goal of this work was not to design or manufacture a manually adjustable light shelf but to create a knowledge-base, which in turn would help a manufacturer produce one that is optimized for a given location and use. It will also help in the development of user manuals to support such products. Additionally, this work can help users to get the maximum benefit from an adjustable light shelf system by providing them with optimum light shelf configurations. Towards these goals a 'proof of concept' is presented here for an optimized light shelf selection system for a specific location and use.

5.1.1 Framework Outline

The proposed framework will be a selection tool to derive optimal light shelf configurations in a given context. A schematic diagram of the proposed framework is shown in Fig. 88. It consists of two major components: (1) user inputs and (2) the resulting output with various light shelf configuration suggestions. Once the user has provided some basic information about the context of the light shelf the framework will come up with the optimal light shelf configuration using climate based daylighting simulation.

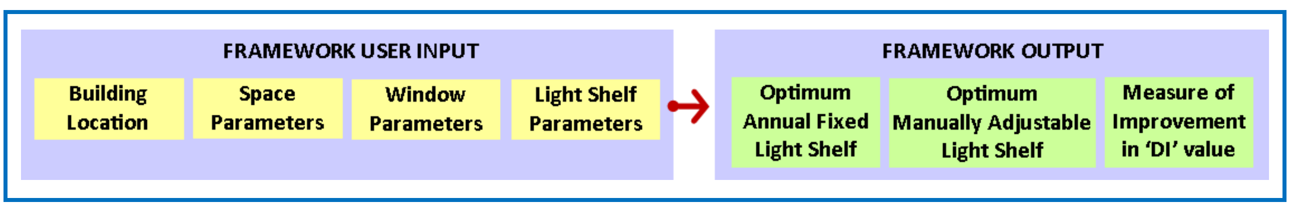


Fig. 88 Diagram of framework for manually adjustable light shelf system.

5.1.2 Components of the Framework

The framework developed for this research is a proof-of-concept for an envisioned selection tool. A schematic diagram of the front-end of the proposed framework, its possible graphical user interface (GUI), is shown in Fig. 89.

The framework allows users to input some basic values related to the context of their light shelf configuration and scenario. Based on these inputs it then calculates variations of configurations and suggests the possible optimum light shelf configurations for both an annually fixed and a seasonally adjustable version. It also provides a numeric indication of light shelf performance in the form of Daylight Index (DI) values. Based on the selection of the building's location the system accesses the Typical Meteorological Year (TMY) climate file for the location to conduct a climate based daylight performance evaluation of all relevant light shelf configurations.

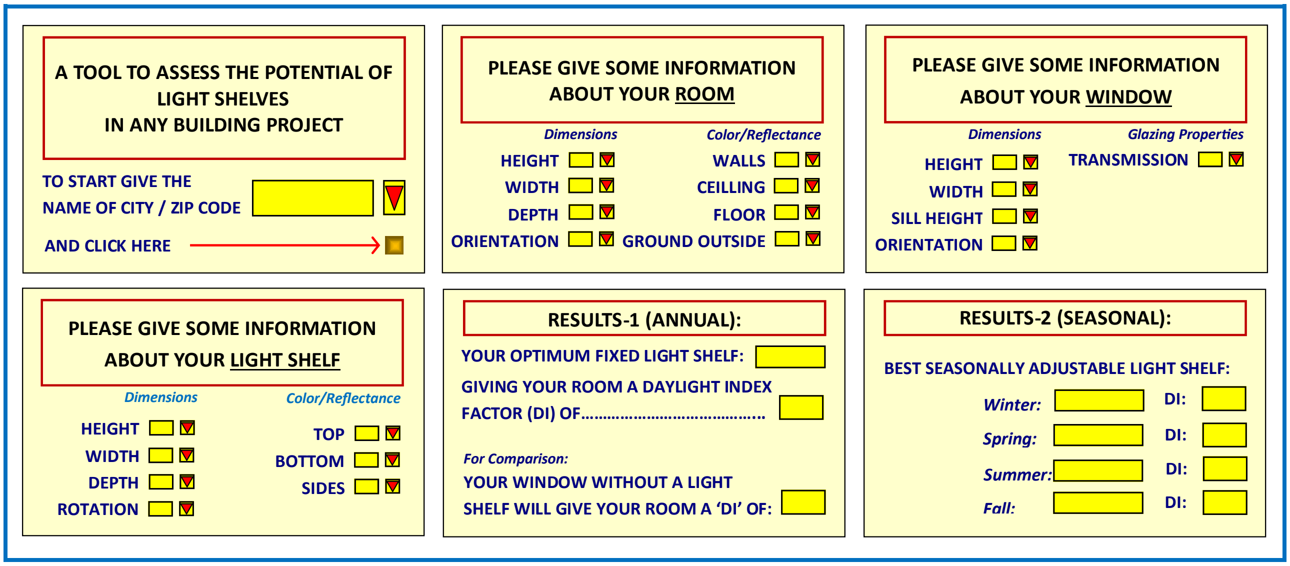


Fig. 89 Schematic layout of the front-end of the proposed framework.

In order to find the optimum light shelf configuration for a given context the user will be asked for input on the following topics:

- Building Location
  - Name of City / Zip Code
- Space with Light Shelf
  - Height
  - Width
  - Depth
  - Orientation of Opening
  - Color (reflectance) of room enclosure (walls, roof, floor)
- Window with Light Shelf
  - Height
  - Width
  - Sill Height
  - Over-all Transmission of the Window Opening
- Light Shelf

- Height
- Width
- Depth (outside & inside)
- Rotation (outside & inside)
- Reflectance of the Light Shelf Bounding Surfaces (top, bottom, sides)

- Lighting Preferences
  - What is the Target Indoor Illumination Level (threshold value in lux)
  - Perception of Over-lit areas (choose one of the following)
    - Acceptable
    - Doesn’t Matter
    - Some Concern
    - Average Concern
    - Big Concern
    - Severe Concern
    - Avoid
  - Perception of Under-lit areas (choose one of the following)
    - Acceptable
    - Doesn’t Matter
    - Some Concern
    - Average Concern
    - Big Concern
    - Severe Concern
    - Avoid

As the premise of this study is to suggest optimally performing, manually adjustable light shelf configurations, the choice of variables that will be allowed as input into the framework will consequently be limited. Users will have the option to input light shelf variables pertaining to a single light shelf or a limited range of variables. In the first case the framework will report the performance of a single light shelf while, in case of the second, a range of light shelf configurations will be presented, where the framework identifies the best solution in terms of DI values. For the second case the database will return with a suggested optimized solution for a ‘fixed light shelf’ that would stay stationary throughout the year and an ‘adjustable light shelf’ that is meant to be re-positioned seasonally four times a year.

5.1.3 Validation of Framework

The framework developed in this research would allow users and manufacturers of light shelves to find optimized fixed or seasonally adjustable light shelf configurations for their specific context. There are a number of similar design assistance tools in the market which corroborate the usefulness of such a framework. The following sections discuss a few examples of such design assistance tools.

5.1.3.1 Building Design Advisor

The Building Design Advisor (BDA) from Lawrence Berkeley National Laboratory (LBNL) is an example of a software environment that has been developed as a design assistance tool for building professionals (Papamichael et al., 1996). It allows users to quickly design a building using its built-in database of components and analyze the result in terms daylighting and energy use. The BDA has a library of intelligent building components where the geometric properties of the components have performance information associated with them. This allows the users to quickly create multiple design options for a project and evaluate them for performance (Fig. 90). Thus BDA acts as a 'decision desktop', helping the user make informed choices for the design of a building.

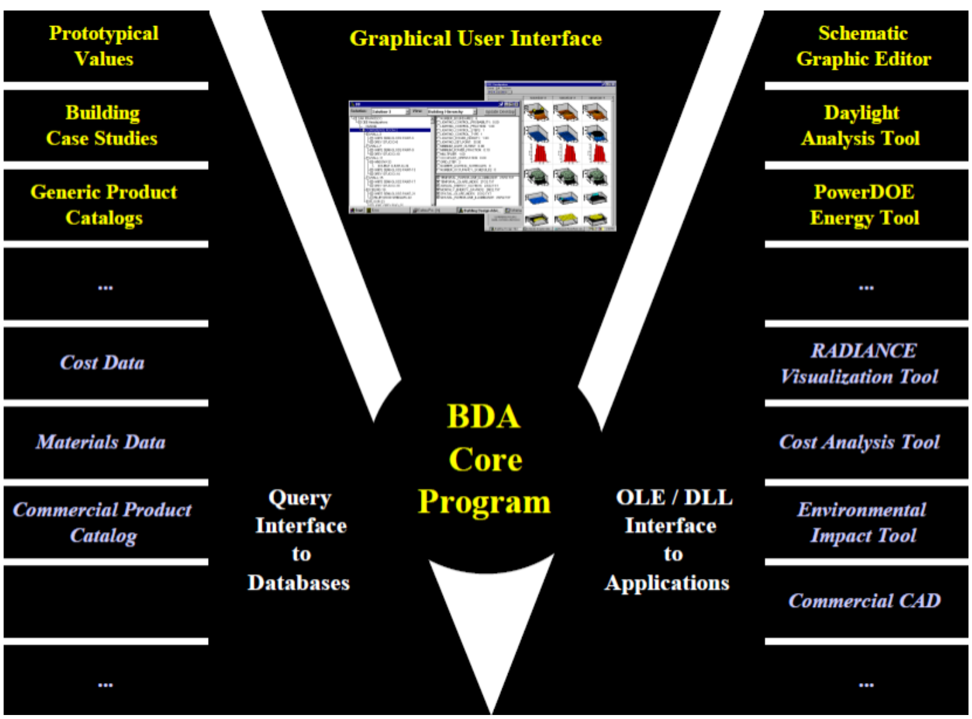


Fig. 90 BDA from LBNL (Papamichael et al., 1996), Used under fair use 2014

5.1.3.2 An interactive expert system for daylighting design exploration

Gagne has proposed an interactive expert system that would guide the designer towards a more efficient daylighting strategy (Gagne et al., 2011). This expert system is intended to be used in the schematic phase of a building design as a 'decision making framework'. Acting like a 'virtual daylighting consultant', this tool helps the designer make informed choices regarding daylighting schemes that would improve the daylighting performance of their building. The expert system has two major parts. The first unit is a repository of knowledge about the possible effect of various design decisions on the daylighting performance. The second part consists of a rule-based design assistant which indicates possible design changes that would improve the daylighting potential of the design. This example validates the framework-development presented in this research in terms of a tool that assists the building professional select an appropriate solution. However, its 'repository of knowledge' or ability to suggest design changes for improved performance do not find a direct parallel in the framework suggested in the present research.

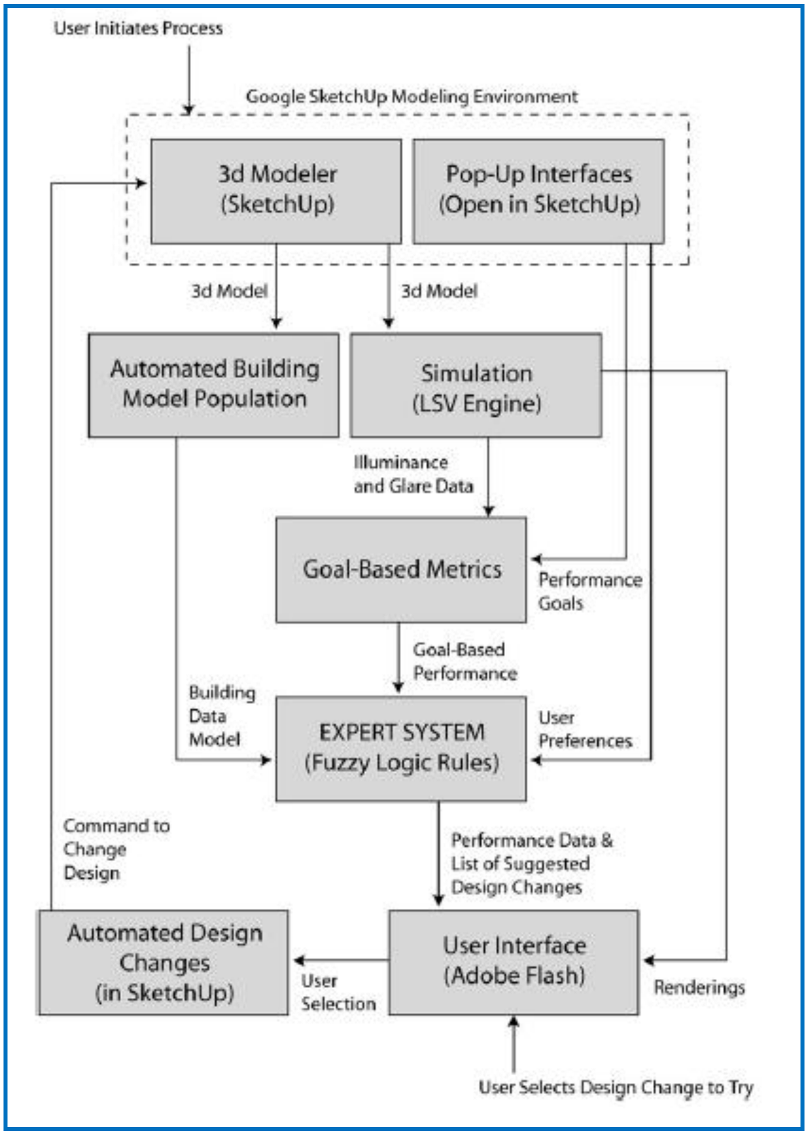


Fig. 91 A daylighting expert system.(Gagne, Andersen, & Norford, 2011), Used under fair use 2014.

5.1.3.3 Anidolic Light Shelf System Design Tool

Kleindienst has proposed a design tool to help choose the appropriate anidolic light shelf system for renovation projects (Kleindienst & Andersen, 2006). The guideline suggests an optimal anidolic light shelf configuration based on room size. A data base of possible solutions seems to be present in the back-end of the tool which provides relevant solutions based on the external variable of room size. This is possible because of the limited number of variables involved and this differs from the framework proposed in this research. Nevertheless, it has some parallel to the present research in terms of an intelligent tool to assist in finding appropriate solution from a wide variety of options.

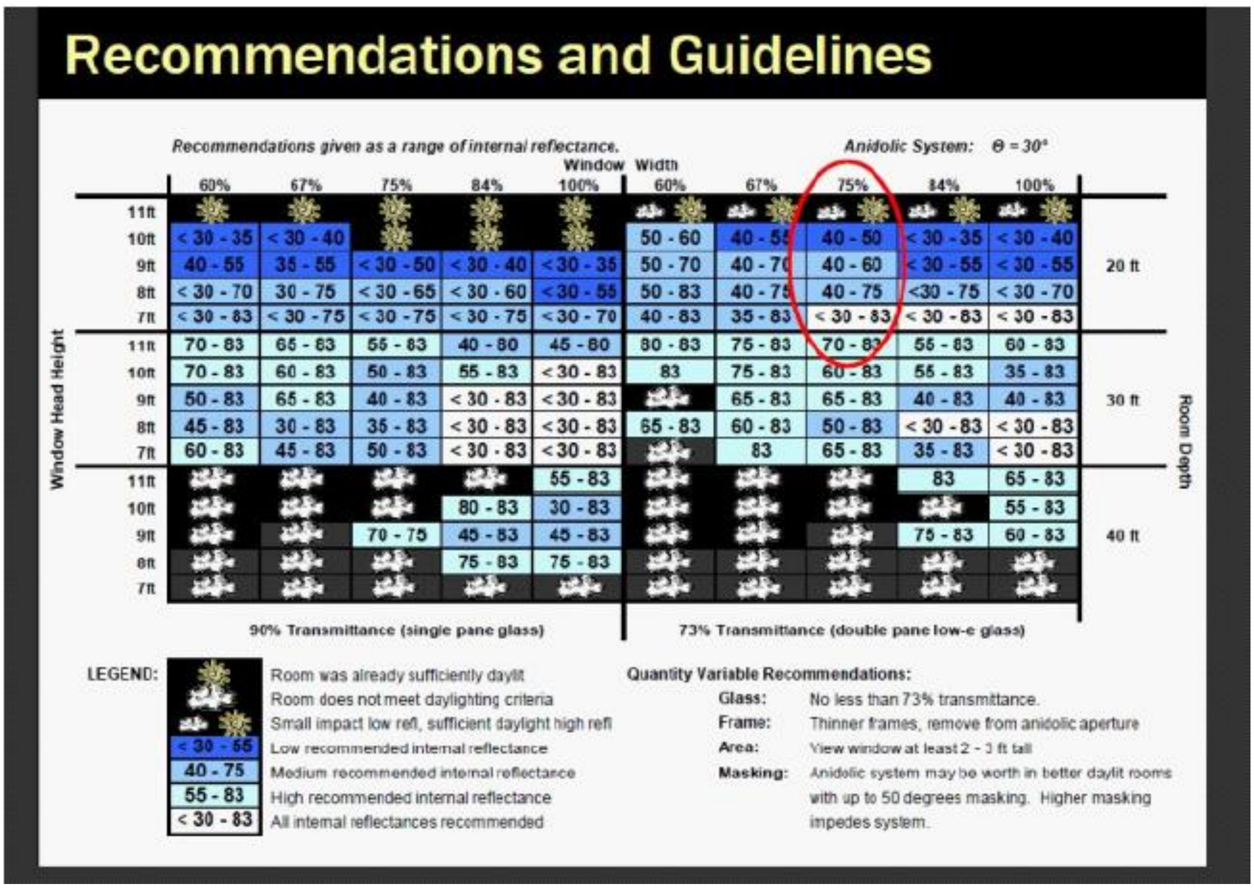


Fig. 92 Anidolic light shelf design guide; (Kleindienst & Andersen, 2006), Used under fair use 2014

Literature review showed many examples of 'design-aid,' like the ones discussed above, which are intended to help building professionals make intelligent choice in the design and construction of the built environment. However, no example of an aid was found that was specifically geared towards the selection of an optimized manually adjustable light shelf system for a given context. This research attempted to fill that gap by providing a framework that could support the development of such a design-aid.

5.2 Summary of Findings

In constructing a framework for the development of manually adjustable light shelf technologies this research asked some primary questions:

- 1. Can an adjustable light shelf give significantly better daylight performance than a fixed one?
- 2. Which adjustability feature has the greatest effect on performance of a light shelf?
- 3. Do segmented light shelves further enhance daylight performance?
- 4. How does orientation of a window affect daylight performance of a light shelf?
- 5. How does latitude affect daylight performance of a light shelf?

For questions 1 and 3 the research found the answers to be affirmative. In other words, for most cases, light shelves were found to improve indoor daylight levels as compared to having no light shelf. This performance was further enhanced with the use of light shelves that can be adjusted on a seasonal basis. Segmented light shelves, i.e. those where the external and the internal segments of the light shelf can be manipulated independently, improved the illumination level even further, but the extent of improvement was not very significant.

For question 2 it was found that the rotational adjustment, in most cases, had the greatest effect on light shelf performance improvement. Adjustment of height was found to have the least effect on light shelf performance while a change of depth had some effect on performance but not to the extent rotational adjustment had.

For question 4, it was seen that light shelves were most effective in the southern orientation. This was predictable as the southern exposure has the most sunlight in the northern hemisphere. However, it was interesting to find that light shelves had a significant effect in enhancing indoor daylight levels even in the northern orientation. This makes sense when one notes that daylight performance in this research has been based primarily on the ‘well-lit’ category and north-facing openings have been a traditional favorite of painters for its even ‘north-light’ lasting most of the day. Light shelves also improved indoor daylight levels in the east and the west orientations but to a lesser extent.

As for question 5, light shelves were found to contribute to improved daylight levels at all latitudes with more effect in regions closer to the equator for most orientations.

5.3 Limitations of the Study

This research is limited to the development of a framework for daylighting technologies that fall under the general category of 'light shelves'. This study has focused on light shelves versus other shading systems as they allow an uninterrupted view to the outside, while harvesting daylight for interior use.

This study presents a 'proof of concept' for a framework to support the design of a manually adjustable light shelf system. As a result, only a limited number of system and context variables have been used in this study

In the proposed framework, once the number of user-provided values goes beyond just a few parameters, the set of resulting light shelf configurations can quickly become staggering, possibly challenging the computing power of a user's computer system. A possible solution to this limitation could be to make the framework cloud-based, shifting the calculation-intensive parts of the process to powerful off-site systems. Another solution would be to pre-calculate the performance results of sets of categorized light shelf configurations and provide it packaged within the framework or a database system. In this case, the user-provided context variables will be used to sort and optimize against pre-assembled performance values stored in the data-base of light shelf configurations.

The research did not go into the thermal, energy and cost issues of light shelves which are all very important factors and must be explored to assess the viability of manually adjustable light shelves. This study simply illustrates a methodology by which additional explorations, found necessary in the design and production phase of manually adjustable light shelve, can be undertaken.

It is apparent from the work done so far in this research that adjustable light shelves can have a significant impact on indoor illumination levels. Issues that may have significant impact on light shelf performance but not addressed in this research include:

- Profile shape of light shelves
- Color and reflectivity of light shelf surfaces
- Material of light shelves
- Constructability of shelves

For successful marketing of adjustable light shelves, many factors, not touched upon in this study, will come into play, including:

- Initial cost and operating cost - return on investment
- Ease of operation

Finally, to achieve visual comfort in an indoor space one has to have light of adequate quantity as well as quality. Minimizing unacceptably high contrast ratio (glare) in an indoor environment is therefore critical for a successful luminous interior. The issue of glare has not been addressed directly in this study and can be taken up in future investigations.

5.4 Research Contribution

This research documents and establishes a functional and measurable inter-relationship between a set of system variables for manually adjustable light shelf systems and their effect on harvested daylight in an interior space. Such a relationship can be used to produce market-specific configurations for light shelf developers and manufacturers.

As a second contribution the same functional model, presented in the form of a framework, can be subsequently utilized to deploy daylight-optimized user configuration scenarios for a given context. As the focus is on manually adjustable systems, the variables selected for investigation are those that can be easily manipulated by users or maintenance personnel, utilizing only relatively simple tools. Such variables include the rotation, height and depth of an adjustable light shelf system. The visual performance of these variables in terms of their effect on interior illumination is documented under various seasons, orientations and geographic locations.

5.5 Future Work

Fixed light shelves have been in use over a long period of time. However, there is great potential, as shown by this research, to introduce the feature of manual adjustability, thereby extending their usefulness even further. There are other areas of inquiry not covered by this research that can extend the development of light shelves further. Some of these are discussed below as potential topics of research in the future:

- User interaction with manually adjustable light shelf systems can be a very expansive topic of research. Performance benefits of a manually adjustable light shelf system are largely dependent on the willingness of the occupants to diligently make the necessary adjustments. Motivation for doing so will improve if there is a feedback mechanism that makes the achieved benefits visible to the occupants making the adjustments. A reminder that alerts the responsible person about the impending need for adjustments can also help.

- The effect of light shelves as a shading mechanism is also a research topic of great potential. If properly calibrated, light shelves can have a significant impact on reducing the heating and cooling load of a building. This will translate into additional savings beyond what is derived from introducing daylight into interiors. The issues of payback-period and return on investment can be an extension of this research.
- The role light shelves can play in enhancing buoyancy-driven, single-sided natural ventilation in a building can be another area of fruitful research. Light shelves tend to divide the exterior opening into an upper and a lower part. The design of these two sections can be done in a way so that the lower portion facilitates introduction of cool outside air into the interior space while the upper portion acts as an exhaust for hot indoor air.
- Another potential extension to this research will be to look at parameters on light shelf performance that are not covered in this study. This list may include topics such as profile-shape, color, specularity, and transparency of light shelves and their effect on performance.
- The topic of glare-control has also not been directly addressed in this research and can be a topic of future investigation.
- Three-dimensional printing of complex light shelf geometries and testing them inside artificial skies can be an exciting extension to the experimental methodology used in this study. Making and testing the best light shelf designs as full-scale mock-ups in real settings will be a great reality check and a useful next step in the study of light shelves.

Bibliography:

Abdulmohsen, A. (1995). *Visual and energy performance of lightshelf daylighting systems for office buildings in a hot and arid climate.* (Ph.D.), Texas A&M University, United States -- Texas.

Al-Maiyah, S., & Elkadi, H. (2007). The role of daylight in preserving identities in heritage context. In 73 (Ed.), *Renewable and Sustainable Energy Reviews* (Vol. 11, pp. 1544-1557).

Al-Marwaee, M., & Carter, D. (2006). Tubular guidance systems for daylight: Achieved and predicted installation performances. *Applied Energy, 83*(7), 774-788. doi: DOI: 10.1016/j.apenergy.2005.08.001

Al-Sallal, K. A. (1998). Sizing windows to achieve passive cooling, passive heating, and daylighting in hot arid regions. In 257 (Ed.), *Renewable Energy* (Vol. 14, pp. 365-371).

Al-Shareef, F. M., Oldham, D. J., & Carter, D. J. (2001). A computer model for predicting the daylight performance of complex parallel shading systems. *Building and Environment, 36*(5), 605-618. doi: Doi: 10.1016/s0360-1323(00)00084-6

Altan, H., Ward, I., Mohelnikova, J., & Vajkay, F. (2009). An internal assessment of the thermal comfort and daylighting conditions of a naturally ventilated building with an active glazed facade in a temperate climate. *Energy and Buildings, 41*(1), 36-50. doi: DOI: 10.1016/j.enbuild.2008.07.009

Alzoubi, H., Al-Rqaibat, S. a., & Bataineh, R. F. (2010). Pre-versus post-occupancy evaluation of daylight quality in hospitals. *Building and Environment, 45*(12), 2652-2665. doi: DOI: 10.1016/j.buildenv.2010.05.027

Alzoubi, H. H., & Al-Zoubi, A. H. (2010). Assessment of building façade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades. *Energy Conversion and Management, 51*(8), 1592-1599. doi: DOI: 10.1016/j.enconman.2009.08.039

Anderson, B., Adegran, M., Webster, T., Place, W., Kammaured, R., & Albrand, P. (1987). Effects of Daylighting Options on the Energy Performance of Two Existing Passive Commercial Buildings. In 301 (Ed.), (Vol. 22, pp. 3-12). Building and Environment.

Athienitis, A. K., & Tzempelikos, A. (2002). A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device. *Solar Energy, 72*(4), 271-281. doi: Doi: 10.1016/s0038-092x(02)00016-6

Baetens, R., Jelle, B. P., & Gustavsen, A. (2010). Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. *Solar Energy Materials and Solar Cells, 94*(2), 87-105. doi: DOI: 10.1016/j.solmat.2009.08.021

Baroncini, C., Boccia, O., Chella, F., & Zazzini, P. (2010). Experimental analysis on a 1:2 scale model of the double light pipe, an innovative technological device for daylight transmission. *Solar Energy, 84*(2), 296-307. doi: DOI: 10.1016/j.solener.2009.11.011

Belakehal, A., Tabet Aoul, K., & Bennadji, A. (2004). Sunlighting and daylighting strategies in the traditional urban spaces and buildings of the hot arid regions. *Renewable Energy, 29*(5), 687-702. doi: DOI: 10.1016/j.renene.2003.09.001

Benton, C. (1990). *Daylighting in the U.S., Trends, Technology and Design.* Paper presented at the Second European Conference on Architecture, Paris.

Bhavani, R. G. a. M. A. K. (2011). Advanced lighting simulation tools for daylighting purpose: Powerful features and related issues. *Trends Applied Sci. Res., 6*(4), 345-365. doi: 10.3923/tasr.2011.345.363

Calcagni, B., Filippetti, F., & Paroncini, M. (2000). Daylighting Analysis of an Atrium Building. In 170 (Ed.), *World Renewable Energy Congress VI* (pp. 645-648). Oxford: Pergamon.

Calcagni, B., & Paroncini, M. (2004). Daylight factor prediction in atria building designs. *Solar Energy, 76*(6), 669-682. doi: DOI: 10.1016/j.solener.2004.01.009

Canziani, R., Peron, F., & Rossi, G. (2004). Daylight and energy performances of a new type of light pipe. *Energy and Buildings, 36*(11), 1163-1176. doi: DOI: 10.1016/j.enbuild.2004.05.001

Capeluto, I. G. (2003). The influence of the urban environment on the availability of daylighting in office buildings in Israel. *Building and Environment, 38*(5), 745-752. doi: Doi: 10.1016/s0360-1323(02)00238-x

Chain, C., Dumortier, D., & Fontoynont, M. (2001). Consideration of daylight's colour. *Energy and Buildings, 33*(3), 193-198. doi: Doi: 10.1016/s0378-7788(00)00081-5

Chaiwiwatworakul, P., Chirarattananon, S., & Rakkwamsuk, P. (2009). Application of automated blind for daylighting in tropical region. *Energy Conversion and Management, 50*(12), 2927-2943. doi: DOI: 10.1016/j.enconman.2009.07.008

Chel, A., Tiwari, G. N., & Chandra, A. (2009). A model for estimation of daylight factor for skylight: An experimental validation using pyramid shape skylight over vault roof mud-house in New Delhi (India). *Applied Energy, 86*(11), 2507-2519. doi: DOI: 10.1016/j.apenergy.2009.03.004

Chel, A., Tiwari, G. N., & Singh, H. N. (2010). A modified model for estimation of daylight factor for skylight integrated with dome roof structure of mud-house in New Delhi (India). *Applied Energy, 87*(10), 3037-3050. doi: DOI: 10.1016/j.apenergy.2010.02.018

Chirarattananon, S., Chaiwiwatworakul, P., & Pattanasethanon, S. (2002). Daylight availability and models for global and diffuse horizontal illuminance and irradiance for Bangkok. *Renewable Energy, 26*(1), 69-89. doi: Doi: 10.1016/s0960-1481(01)00099-4

Chirarattananon, S., Chedsiri, S., & Renshen, L. (2000). Daylighting through light pipes in the tropics. *Solar Energy, 69*(4), 331-341. doi: Doi: 10.1016/s0038-092x(00)00081-5

Christoffersen, J. (1995). *SBI-report 258: Daylight Utilisation in Office Buildings* . (Ph.D. thesis), Statens Byggeforskningsinstitut, Hørsholm, Denmark.

Claros, S.-T., & Soler, A. (2001). Indoor daylight climate-comparison between light shelves and overhang performances in Madrid for hours with unit sunshine fraction and realistic values of model reflectance. *Solar Energy, 71*(4), 233-239. doi: Doi: 10.1016/s0038-092x(01)00046-9

Claros, S.-T., & Soler, A. (2002). Indoor daylight climate-influence of light shelf and model reflectance on light shelf performance in Madrid for hours with unit sunshine fraction. *Building and Environment, 37*(6), 587-598. doi: Doi: 10.1016/s0360-1323(01)00074-9

Clevenger, C. M., & Haymaker, J. (2009). Framework and Metrics for Assessing the Guidance of Design Processes. In 317 (Ed.). International comference on Engineering Design, ICED'09, 24-27 August 2009, Stanford University, Stanford, CA, USA.

Close, J. (1996). Optimising daylighting in high-rise commercial developments in SE Asia and the use of computer programmes as a design tool. In 254 (Ed.), *Renewable Energy* (Vol. 8, pp. 206-209).

Cole, R. J. (1990). The effect of the surfaces enclosing atria on the daylight in adjacent spaces. *Building and Environment, 25*(1), 37-42. doi: Doi: 10.1016/0360-1323(90)90039-t

Compagnon, R. (2004). Solar and daylight availability in the urban fabric. *Energy and Buildings, 36*(4), 321-328. doi: DOI: 10.1016/j.enbuild.2004.01.009

De Rosa, A., Ferraro, V., Igawa, N., Kaliakatsos, D., & Marinelli, V. (2009). INLUX: A calculation code for daylight illuminance predictions inside buildings and its experimental validation. *Building and Environment, 44*(8), 1769-1775. doi: DOI: 10.1016/j.buildenv.2008.11.014

DiLaura, D., Houser, K., Mistrick, R., & Steffy, G. (Eds.). (2011). *The IES Lighting Handbook, Tenth Edition* (10th ed.): Illuminating Engineering Society.

Djamila, H., Ming, C. C., & Kumaresan, S. (2011). Estimation of exterior vertical daylight for the humid tropic of Kota Kinabalu city in East Malaysia. In 12 (Ed.), *Renewable Energy* (Vol. 36, pp. 9-15).

Doulos, L., Tsangrassoulis, A., & Topalis, F. (2008). Quantifying energy savings in daylight responsive systems: The role of dimming electronic ballasts. *Energy and Buildings, 40*(1), 36-50. doi: DOI: 10.1016/j.enbuild.2007.01.019

Doulos, L., Tsangrassoulis, A., & Topalis, F. V. (2008). The role of spectral response of photosensors in daylight responsive systems. *Energy and Buildings, 40*(4), 588-599. doi: DOI: 10.1016/j.enbuild.2007.04.010

Du, J., & Sharples, S. (2010). Analysing the impact of reflectance distributions and well geometries on vertical surface daylight levels in atria for overcast skies. *Building and Environment, 45*(7), 1733-1745. doi: DOI: 10.1016/j.buildenv.2010.01.026

Earp, A. A., Smith, G. B., Franklin, J., & Swift, P. (2004). Optimisation of a three-colour luminescent solar concentrator daylighting system. *Solar Energy Materials and Solar Cells, 84*(1-4), 411-426. doi: DOI: 10.1016/j.solmat.2004.02.046

Edmonds, I. R., & Greenup, P. J. (2002). Daylighting in the tropics. *Solar Energy, 73*(2), 111-121. doi: Doi: 10.1016/s0038-092x(02)00039-7

El Sheikh, M. (2012). Parametric-based algorithm for kinetic facades design and daylighting performance integration. In 323 (Ed.). M.B.S. dissertation, University of Southern California, United States -- California.

Fairuz Syed Fadzil, S., & Sia, S.-J. (2004). Sunlight control and daylight distribution analysis: the KOMTAR case study. *Building and Environment, 39*(6), 713-717. doi: DOI: 10.1016/j.buildenv.2003.12.009

Fakra, A. H., Miranville, F., Boyer, H., & Guichard, S. (2011). Development of a new model to predict indoor daylighting: Integration in CODYRUN software and validation. In 11 (Ed.), *Energy Conversion and Management* (Vol. 52, pp. 2724-2734).

Fontoynont, M. (2002). Perceived performance of daylighting systems: lighting efficacy and agreeableness. *Solar Energy, 73*(2), 83-94. doi: Doi: 10.1016/s0038-092x(02)00035-x

Fontoynont, M., Place, W., & Bauman, F. (1984). Impact of electric lighting efficiency on the energy saving potential of daylighting from roof monitors. *Energy and Buildings, 6*(4), 375-386. doi: Doi: 10.1016/0378-7788(84)90020-3

Freewan, A. A., Shao, L., & Riffat, S. (2009). Interactions between louvers and ceiling geometry for maximum daylighting performance. *Renewable Energy, 34*(1), 223-232. doi: DOI: 10.1016/j.renene.2008.03.019

Gagne, J. M. L., Andersen, M., & Norford, L. K. (2011). An interactive expert system for daylighting design exploration. *Building and Environment, 46*(11), 2351-2364. doi: 10.1016/j.buildenv.2011.05.016

Galasiu, A. D., Atif, M. R., & MacDonald, R. A. (2004). Impact of window blinds on daylight-linked dimming and automatic on/off lighting controls. *Solar Energy, 76*(5), 523-544. doi: DOI: 10.1016/j.solener.2003.12.007

Garcia-Hansen, V., Esteves, A., & Pattini, A. (2002). Passive solar systems for heating, daylighting and ventilation for rooms without an equator-facing facade. *Renewable Energy, 26*(1), 91-111. doi: Doi: 10.1016/s0960-1481(01)00089-1

Grant, E. J., & Jones, J. R. (2005). A Decision-Making Approach to Green Roof System Design. In 318 (Ed.).

Greenup, P. J., & Edmonds, I. R. (2004). Test room measurements and computer simulations of the micro-light guiding shade daylight redirecting device. In 251 (Ed.), *Solar Energy* (Vol. 76, pp. 99-109).

Gugliermetti, F., & Bisegna, F. (2006). Daylighting with external shading devices: design and simulation algorithms. *Building and Environment, 41*(2), 136-149. doi: DOI: 10.1016/j.buildenv.2004.12.011

Haglund, K. L. (2010). Decision-making Methodology & Selection Tools for High-performance Window Systms in U.S. Climates. In 316 (Ed.). BEST2 - Strategic Issues in Building Desing - Session WB13-4.

Han, H., & Tai Kim, J. (2010). Application of high-density daylight for indoor illumination. *Energy, 35*(6), 2654-2666. doi: DOI: 10.1016/j.energy.2009.05.037

Heschong, L. (2012). PIER Daylight Metrics Final Report.

Ho, M.-C., Chiang, C.-M., Chou, P.-C., Chang, K.-F., & Lee, C.-Y. (2008). Optimal sun-shading design for enhanced daylight illumination of subtropical classrooms. *Energy and Buildings, 40*(10), 1844-1855. doi: DOI: 10.1016/j.enbuild.2008.04.012

Hongbing, W., Jun, Q., Yonghong, H., & Li, D. (2010). Optimal tree design for daylighting in residential buildings. *Building and Environment, 45*(12), 2594-2606. doi: DOI: 10.1016/j.buildenv.2010.05.019

Hua, Y., Oswald, A., & Yang, X. (2011). Effectiveness of daylighting design and occupant visual satisfaction in a LEED Gold laboratory building. In 10 (Ed.), *Building and Environment* (Vol. 46, pp. 54-64).

Hviid, C. A., Nielsen, T. R., & Svendsen, S. (2008). Simple tool to evaluate the impact of daylight on building energy consumption. *Solar Energy, 82*(9), 787-798. doi: DOI: 10.1016/j.solener.2008.03.001

Ihm, P., Nemri, A., & Krarti, M. (2009). Estimation of lighting energy savings from daylighting. *Building and Environment, 44*(3), 509-514. doi: DOI: 10.1016/j.buildenv.2008.04.016

Inoue, T. (2003). Solar shading and daylighting by means of autonomous responsive dimming glass: practical application. *Energy and Buildings, 35*(5), 463-471. doi: Doi: 10.1016/s0378-7788(02)00143-3

Inoue, T., Ichinose, M., & Ichikawa, N. (2008). Thermotropic glass with active dimming control for solar shading and daylighting. *Energy and Buildings, 40*(3), 385-393. doi: DOI: 10.1016/j.enbuild.2007.03.006

Iversen, A., Roy, N., Hvass, M., Jorgensen, M., Christoffersen, J., and, W. O., & Johnsen, K. (2013). Daylight Calculations in Practice. Copenhagen, Denmark: Danish Building Research Institute, Aalborg University.

Jakubiec, J. A. (2012). Daylight Simulation Software. Retrieved from http://diva4rhino.com/profiles/blogs/daylight-simulation-software

Johnsen, K. (2000). Daylight in buildings, collaborative research in the International Energy Agency (IEA Task 21). In 250 (Ed.), *Renewable Energy* (Vol. 15, pp. 142-150).

Johnson, R., Sullivan, R., Selkowitz, S., Nozaki, S., Conner, C., & Arasteh, D. (1984). Glazing energy performance and design optimization with daylighting. *Energy and Buildings, 6*(4), 305-317. doi: Doi: 10.1016/0378-7788(84)90014-8

Joon-Ho Choi, Liliana O. Beltran, & Kim, H.-S. (2011). Impacts of indoor daylight environments on patient average length of stay

(ALOS) in a healthcare facility. In 300 (Ed.). Building and Environment: Building and Environment.

Joshi, M., Sawhney, R. L., & Buddhi, D. (2007). Estimation of Luminous efficacy of daylight and exterior illuminance for composite climate of Indore city in Mid Western India. *Renewable Energy, 32*(8), 1363-1378. doi: DOI: 10.1016/j.renene.2006.06.003

Kapsis, K., Tzempelikos, A., Athienitis, A. K., & Zmeureanu, R. G. (2010). Daylighting performance evaluation of a bottom-up motorized roller shade. *Solar Energy, 84*(12), 2120-2131. doi: DOI: 10.1016/j.solener.2010.09.004

Kazanasmaz, T., Günaydin, M., & Binol, S. (2009). Artificial neural networks to predict daylight illuminance in office buildings. *Building and Environment, 44*(8), 1751-1757. doi: DOI: 10.1016/j.buildenv.2008.11.012

Kim, G., & Kim, J. T. (2010). Healthy-daylighting design for the living environment in apartments in Korea. *Building and Environment, 45*(2), 287-294. doi: DOI: 10.1016/j.buildenv.2009.07.018

Kim, J. T., & Kim, G. (2010). Overview and new developments in optical daylighting systems for building a healthy indoor environment. *Building and Environment, 45*(2), 256-269. doi: DOI: 10.1016/j.buildenv.2009.08.024

Kischkoweit-Lopin, M. (2002). An overview of daylighting systems. *Solar Energy, 73*(2), 77-82. doi: Doi: 10.1016/s0038-092x(02)00036-1

Kleindienst, S., & Andersen, M. (2006). Improving Daylighting in Existing Buildings: Characterizing the Effect of Anidolic Systems. *SOLAR 2006: Renewable Energy - Key to Climate Recovery*.

Kocifaj, M. (2009). Analytical solution for daylight transmission via hollow light pipes with a transparent glazing. *Solar Energy, 83*(2), 186-192. doi: DOI: 10.1016/j.solener.2008.07.012

Koo, S. Y., Yeo, M. S., & Kim, K. W. (2010). Automated blind control to maximize the benefits of daylight in buildings. *Building and Environment, 45*(6), 1508-1520. doi: DOI: 10.1016/j.buildenv.2009.12.014

Kristl, Z., & Krainer, A. (1999). LIGHT WELLS IN RESIDENTIAL BUILDING AS A COMPLEMENTARY DAYLIGHT SOURCE. *Solar Energy, 65*(3), 197-206. doi: Doi: 10.1016/s0038-092x(98)00127-3

Krüger, E. L., & Dorigo, A. L. (2008). Daylighting analysis in a public school in Curitiba, Brazil. *Renewable Energy, 33*(7), 1695-1702. doi: DOI: 10.1016/j.renene.2007.09.002

Kumaragurabaran, V. (2012). *High Dynamic Range Image Processing Toolkit for Lightng Simulations and Analysis.* (Master of Science in Architecture, Design Computing), University of Washington, Seattle.

Lam, J. C., & Li, D. H. W. (1999). An analysis of daylighting and solar heat for cooling-dominated office buildings. *Solar Energy, 65*(4), 251-262. doi: Doi: 10.1016/s0038-092x(98)00136-4

Lee, E. S., DiBartolomeo, D. L., & Selkowitz, S. E. (1998). Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office. *Energy and Buildings, 29*(1), 47-63. doi: Doi: 10.1016/s0378-7788(98)00035-8

Lee, E. S., DiBartolomeo, D. L., & Selkowitz, S. E. (2006). Daylighting control performance of a thin-film ceramic electrochromic window: Field study results. *Energy and Buildings, 38*(1), 30-44. doi: DOI: 10.1016/j.enbuild.2005.02.009

Lee, E. S., & Selkowitz, S. E. (2006). The New York Times Headquarters daylighting mockup: Monitored performance of the daylighting control system. *Energy and Buildings, 38*(7), 914-929. doi: DOI: 10.1016/j.enbuild.2006.03.019

Leslie, R. P. (2003). Capturing the daylight dividend in buildings: why and how? *Building and Environment, 38*(2), 381-385. doi: Doi: 10.1016/s0360-1323(02)00118-x

Li, D. H. W. (2010). A review of daylight illuminance determinations and energy implications. *Applied Energy, 87*(7), 2109-2118. doi: DOI: 10.1016/j.apenergy.2010.03.004

Li, D. H. W., Cheung, G. H. W., Cheung, K. L., & Lam, J. C. (2009). Simple method for determining daylight illuminance in a heavily obstructed environment. *Building and Environment, 44*(5), 1074-1080. doi: DOI: 10.1016/j.buildenv.2008.07.011

Li, D. H. W., Cheung, G. H. W., Cheung, K. L., & Lam, T. N. T. (2010). Determination of vertical daylight illuminance under non-overcast sky conditions. *Building and Environment, 45*(2), 498-508. doi: DOI: 10.1016/j.buildenv.2009.07.008

Li, D. H. W., & Tsang, E. K. W. (2008). An analysis of daylighting performance for office buildings in Hong Kong. *Building and Environment, 43*(9), 1446-1458. doi: DOI: 10.1016/j.buildenv.2007.07.002

Li, D. H. W., & Wong, S. L. (2007). Daylighting and energy implications due to shading effects from nearby buildings. *Applied Energy, 84*(12), 1199-1209. doi: DOI: 10.1016/j.apenergy.2007.04.005

Lindelöf, D. (2009). A fast daylight model suitable for embedded controllers. *Solar Energy, 83*(1), 57-68. doi: DOI: 10.1016/j.solener.2008.06.008

Linhart, F., & Scartezzini, J.-L. (2010). Minimizing lighting power density in office rooms equipped with Anidolic Daylighting Systems. *Solar Energy, 84*(4), 587-595. doi: DOI: 10.1016/j.solener.2009.05.001

Linhart, F., Wittkopf, S. K., & Scartezzini, J.-L. (2010). Performance of Anidolic Daylighting Systems in tropical climates - Parametric studies for identification of main influencing factors. *Solar Energy, 84*(7), 1085-1094. doi: DOI: 10.1016/j.solener.2010.01.014

Littlefair, P. (1996). Designing with Innovative Daylighting *BR305*: Construction Research Communications, Garston, UK.

Littlefair, P. (2001). Daylight, sunlight and solar gain in the urban environment. *Solar Energy, 70*(3), 177-185. doi: Doi: 10.1016/s0038-092x(00)00099-2

Littlefair, P. (2002). Daylight prediction in atrium buildings. *Solar Energy, 73*(2), 105-109. doi: Doi: 10.1016/s0038-092x(02)00038-5

Littlefair, P. J., Aizlewood, M. E., & Birtles, A. B. (1994). The performance of innovative daylighting systems. *Renewable Energy, 5*(5-8), 920-934. doi: Doi: 10.1016/0960-1481(94)90113-9

Lorenz, W. (2001). A glazing unit for solar control, daylighting and energy conservation. *Solar Energy, 70*(2), 109-130. doi: Doi: 10.1016/s0038-092x(00)00132-8

Lowry, G., & Thomas, S. (2010). Spreadsheet-based calculation tool for direct daylight illuminance adaptable for different glazing properties and sky models. *Building and Environment, 45*(4), 1081-1086. doi: DOI: 10.1016/j.buildenv.2009.09.017

Ma'bdeh, S. N. (2011). A Decisioin-Support Framework for the Design and Application of Radiant Cooling System. In 319 (Ed.). Phd Dissertation, Virginia Tech.

Manz, H., Egolf, P. W., Suter, P., & Goetzberger, A. (1997). TIM-PCM external wall system for solar space heating and daylighting. *Solar Energy, 61*(6), 369-379. doi: Doi: 10.1016/s0038-092x(97)00086-8

Mayhoub, M. S., & Carter, D. J. (2011). The costs and benefits of using daylight guidance to light office buildings. In 8 (Ed.), *Building and Environment* (Vol. 46, pp. 698-710).

Molteni, S. C., Courret, G., Paule, B., Michel, L., & Scartezzini, J. L. Design of anidolic zenithal lightguides for daylighting of underground spaces. *Solar Energy, 69*(Supplement 6), 117-129. doi: Doi: 10.1016/s0038-092x(01)00065-2

Nabil, A., & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings, 38*(7), 905-913. doi: DOI: 10.1016/j.enbuild.2006.03.013

Narasimhan, V., & Maitreya, V. K. (1969). The reflected component of daylight in multistoreyed buildings in the tropics. *Building Science, 4*(2), 93-97. doi: Doi: 10.1016/0007-3628(69)90009-7

Navvab, M., Karayel, M., Ne'eman, E., & Selkowitz, S. (1984). Analysis of atmospheric turbidity for daylight calculations. *Energy and Buildings, 6*(3), 293-303. doi: Doi: 10.1016/0378-7788(84)90061-6

Nazzal, A. A. (2001). A new daylight glare evaluation method: Introduction of the monitoring protocol and calculation method. *Energy and Buildings, 33*(3), 257-265. doi: Doi: 10.1016/s0378-7788(00)00090-6

Nielsen, M. V., Svendsen, S., & Jensen, L. B. (2011). Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. In 7 (Ed.), *Solar Energy* (Vol. 85, pp. 757-768).

Nilsson, A. M., & Jonsson, J. C. (2010). Light-scattering properties of a Venetian blind slat used for daylighting applications. In 20 (Ed.), *Solar Energy* (Vol. 84, pp. 2103-2111).

Olbina, S. (2005). Decision-Making Framework for the Selection and Design of Shading Devices. In 314 (Ed.), *Environmental Design and Planning* (Vol. PhD). Blacksburg: Virginia Tech.

Olbina, S., & Beliveau, Y. (2006). Application of 3D Modeling Software for Daylighting Simulation of Shading Devices. In 315 (Ed.). Convr2006: Digital library of construction informatics
and information technology in civil engineering and construction.

Olbina, S., & Beliveau, Y. (2007). Decision-Making Framework for Selection and Design of Shading Devices Based on Daylighting. *Journal of Green Building, 2*(3), 88-105. doi: 10.3992/jgb.2.3.88

Olbina, S., & Beliveau, Y. (2009). Developing a transparent shading device as a daylighting system. *Building Research and Information, 37*(2), 148-163. doi: 10.1080/09613210902723738

Osterhaus, W. K. E. (2005). Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy, 79*(2), 140-158. doi: DOI: 10.1016/j.solener.2004.11.011

Page, J., Scartezzini, J.-L., Kaempf, J., & Morel, N. (2007). On-site performance of electrochromic glazings coupled to an anidolic daylighting system. *Solar Energy, 81*(9), 1166-1179. doi: DOI: 10.1016/j.solener.2007.01.011

Pandharipande, A., & Caicedo, D. (2011). Daylight integrated illumination control of LED systems based on enhanced presence sensing. In 6 (Ed.), *Energy and Buildings* (Vol. 43, pp. 944-950).

Papamichael, K., LaPorta, J., & Chauvet, H. (1997). Building Design Advisor: automated integratin of multiple simulation tools. *Automation in Construction, 6*(1997), 341-352.

Papamichael, K., LaPorta, J., Chauvet, H., Collins, D., Trzeinski, T., Thorpe, J., & Selkowitz, S. (1996). The Building Design Advisor. *Proceedings of the ACADIA 1996 Conference, University of Arizona, Tueson, AZ.*

Park, B.-C., Choi, A.-S., Jeong, J.-W., & Lee, E. S. (2011). Performance of integrated systems of automated roller shade systems and daylight responsive dimming systems. In 5 (Ed.), *Building and Environment* (Vol. 46, pp. 747-757).

Pattanasethanon, S., Lertsatitthanakorn, C., Atthajariyakul, S., & Soponronnarit, S. (2007). All sky modeling daylight availability and illuminance/irradiance on horizontal plane for Mahasarakham, Thailand. *Energy Conversion and Management, 48*(5), 1601-1614. doi: DOI: 10.1016/j.enconman.2006.11.012

Pérez-Burgos, A., de Miguel, A., & Bilbao, J. (2010). Daylight illuminance on horizontal and vertical surfaces for clear skies. Case study of shaded surfaces. In 19 (Ed.), *Solar Energy* (Vol. 84, pp. 137-143).

Piccolo, A., Pennisi, A., & Simone, F. (2009). Daylighting performance of an electrochromic window in a small scale test-cell. *Solar Energy, 83*(6), 832-844. doi: DOI: 10.1016/j.solener.2008.11.013

Polato, P. (2000). Daylight and Solar Energy Characterisation of Glazing Units for Buildings: Implementation of ISO and CEN Standards. In 164 (Ed.), *World Renewable Energy Congress VI* (pp. 219-223). Oxford: Pergamon.

Rakha, T., & Nassar, K. (2011). Genetic algorithms for ceiling form optimization in response to daylight levels. In 4 (Ed.), *Renewable Energy* (Vol. 36, pp. 2348-2356).

Ramos, G., & Ghisi, E. (2010). Analysis of daylight calculated using the EnergyPlus programme. In 18 (Ed.), *Renewable and Sustainable Energy Reviews* (Vol. 14, pp. 1948-1958).

Rao, S. (2011). Thermal and Daylighting Analysis of Building Perimeter Zones Equipped with Combined Dynamic Shading Systems. In 321 (Ed.): Purdue University, West Lafayette, Indiana.

Raphael, B. (2011). Active Control of Daylighting Features in Buildings. In 322 (Ed.), *Computer–Aided Civil and Infrastructure Engineering* (Vol. 26, pp. 393-405).

Reinhart, C., & Fitz, A. (2006). Findings from a survey on the current use of daylight simulations in building design. *Energy and Buildings, 38*(7), 824-835. doi: DOI: 10.1016/j.enbuild.2006.03.012

Reinhart, C. F., & Weissman, D. A. (2012). The daylit area – Correlating architectural student assessments with current and emerging daylight availability metrics. *Building and Environment, 50*, 155-164. doi: 10.1016/j.buildenv.2011.10.024

Reinhart, C. F., & Wienold, J. (2011). The daylighting dashboard - A simulation-based design analysis for daylit spaces. In 3 (Ed.), *Building and Environment* (Vol. 46, pp. 386-396).

Rosemann, A., & Kaase, H. (2005). Lightpipe applications for daylighting systems. *Solar Energy, 78*(6), 772-780. doi: DOI: 10.1016/j.solener.2004.09.002

Rosencrantz, T., Bülow-Hübe, H., Karlsson, B., & Roos, A. (2005). Increased solar energy and daylight utilisation using anti-reflective coatings in energy-efficient windows. *Solar Energy Materials and Solar Cells, 89*(2-3), 249-260. doi: DOI: 10.1016/j.solmat.2004.12.007

Rosenfeld, A. H., & Selkowitz, S. E. (1977). Beam daylighting: an alternative illumination technique. *Energy and Buildings, 1*(1), 43-50. doi: Doi: 10.1016/0378-7788(77)90009-3

Saridar, S., & Elkadi, H. (2002). The impact of applying recent façade technology on daylighting performance in buildings in eastern Mediterranean. *Building and Environment, 37*(11), 1205-1212. doi: Doi: 10.1016/s0360-1323(01)00095-6

Scartezzini, J.-L., & Courret, G. (2002). Anidolic daylighting systems. *Solar Energy, 73*(2), 123-135. doi: Doi: 10.1016/s0038-092x(02)00040-3

Seo, D., Ihm, P., & Krarti, M. (2011). Development of an optimal daylighting controller. In 2 (Ed.), *Building and Environment* (Vol. 46, pp. 1011-1022).

Serra, R. (1998). Chapter 6--Daylighting. *Renewable and Sustainable Energy Reviews, 2*(1-2), 115-155. doi: Doi: 10.1016/s1364-0321(98)00014-8

Sharples, S., Stewart, L., & Tregenza, P. R. (2001). Glazing daylight transmittances: a field survey of windows in urban areas. *Building and Environment, 36*(4), 503-509. doi: Doi: 10.1016/s0360-1323(00)00018-4

Singh, M. C., & Garg, S. N. (2010). Illuminance estimation and daylighting energy savings for Indian regions. In 17 (Ed.), *Renewable Energy* (Vol. 35, pp. 703-711).

Smith, G. B. (2004). Materials and systems for efficient lighting and delivery of daylight. *Solar Energy Materials and Solar Cells, 84*(1-4), 395-409. doi: DOI: 10.1016/j.solmat.2004.02.047

Smith, G. B., Earp, A., Stevens, J., Swift, P., McCredie, G., & Franklin, J. (2000). Materials Properties for Advanced Daylighting in Buildings. In A. A. M. Sayigh (Ed.), *World Renewable Energy Congress VI* (pp. 201-206). Oxford: Pergamon.

Smith, G. B., Yan, W., Hossain, M., & McCredie, G. (1998). Science of daylighting in buildings. In 243 (Ed.), *Renewable Energy* (Vol. 15, pp. 325-330).

Soler, A., & Oteiza, P. (1996). Dependence on solar elevation of the performance of a light shelf as a potential daylighting device. In 242 (Ed.), *Renewable Energy* (Vol. 8, pp. 198-201).

Sweitzer, G. (1993). Three advanced daylighting technologies for offices. *Energy, 18*(2), 107-114. doi: Doi: 10.1016/0360-5442(93)90094-t

Tham, Y., & Muneer, T. (2011). Sol-air temperature and daylight illuminance profiles for the UKCP09 data sets. In 1 (Ed.), *Building and Environment* (Vol. 46, pp. 1243-1250).

Thanachareonkit, A., Scartezzini, J. L., & Andersen, M. (2005). Comparing daylighting performance assessment of buildings in scale models and test modules. *Solar Energy, 79*(2), 168-182. doi: DOI: 10.1016/j.solener.2005.01.011

Tsangrassoulis, A., & Bourdakis, V. (2003). Comparison of radiosity and ray-tracing techniques with a practical design procedure for the prediction of daylight levels in atria. *Renewable Energy, 28*(13), 2157-2162. doi: Doi: 10.1016/s0960-1481(03)00078-8

Tsangrassoulis, A., Pavlou, C., Santamouris, M., Pohl, W., & Scheiring, C. (2001). A new value of average beam solar heat gain coefficient for innovative daylighting systems. *Energy and Buildings, 33*(6), 519-524. doi: Doi: 10.1016/s0378-7788(00)00075-x

Tsangrassoulis, A., & Santamouris, M. (2000). A method to estimate the daylight efficiency of round skylights. *Energy and Buildings, 32*(1), 41-45. doi: Doi: 10.1016/s0378-7788(99)00039-0

Tsangrassoulis, A., Santamouris, M., & Asimakopoulos, D. (1996). Theoretical and experimental analysis of daylight performance for various shading systems. *Energy and Buildings, 24*(3), 223-230. doi: Doi: 10.1016/s0378-7788(96)00981-4

Tsangrassoulis, A., Santamouris, M., Geros, V., Wilson, M., & Asimakopoulos, D. (1999). A METHOD TO INVESTIGATE THE POTENTIAL OF SOUTH-ORIENTED VERTICAL SURFACES FOR REFLECTING DAYLIGHT ONTO OPPOSITELY FACING VERTICAL SURFACES UNDER SUNNY CONDITIONS. *Solar Energy, 66*(6), 439-446. doi: Doi: 10.1016/s0038-092x(99)00018-3

Turnbull, P. W., & Loisos, G. A. (2000). Baselines and Barriers: Current Design Practices in Daylighting *Commercial Building: Technologies, Design, and Performance Analysis*: Pacific Gas and Electric Company.

Van Tichelen, P., De Laet, I., Taeymans, F., & Adams, F. (2000). Energy Savings from the EE-Sylk Daylighting System. In 158 (Ed.), *World Renewable Energy Congress VI* (pp. 657-660). Oxford: Pergamon.

Vartiainen, E. (2001). Electricity benefits of daylighting and photovoltaics for various solar facade layouts in office buildings. *Energy and Buildings, 33*(2), 113-120. doi: Doi: 10.1016/s0378-7788(00)00073-6

Vartiainen, E., Peippo, K., & Lund, P. (2000). Daylight optimization of multifunctional solar facades. *Solar Energy, 68*(3), 223-235. doi: Doi: 10.1016/s0038-092x(99)00072-9

Viljoen, A., Dubiel, J., Wilson, M., & Fontoynont, M. (1997). Investigations for improving the daylighting potential of double-skinned office buildings. In 241 (Ed.), *Solar Energy* (Vol. 59, pp. 179-194).

Wa-Gichia, M. (1998). THE HIGH-RISE OPPOSING FACADE IN CLEAR SKY CONDITIONS--NOT ALWAYS AN "OBSTRUCTION" TO DAYLIGHT. *Solar Energy, 64*(4-6), 179-188. doi: Doi: 10.1016/s0038-092x(98)00100-5

Walkenhorst, O., Luther, J., Reinhart, C., & Timmer, J. (2002). Dynamic annual daylight simulations based on one-hour and one-minute means of irradiance data. *Solar Energy, 72*(5), 385-395. doi: Doi: 10.1016/s0038-092x(02)00019-1

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings, 38*(7), 743-757. doi: DOI: 10.1016/j.enbuild.2006.03.017

Wikipedia. (2014). Brute-force search. Retrieved 12 June 2014, 2014, from http://en.wikipedia.org/wiki/Brute-force_search

Wittkopf, S., Oliver Grobe, L., Geisler-Moroder, D., Compagnon, R., Kämpf, J., Linhart, F., & Scartezzini, J.-L. (2010). Ray tracing study for non-imaging daylight collectors. In 15 (Ed.), *Solar Energy* (Vol. 84, pp. 986-996).

Wittkopf, S. K. (2007). Daylight performance of anidolic ceiling under different sky conditions. *Solar Energy, 81*(2), 151-161. doi: DOI: 10.1016/j.solener.2006.04.002

Wittkopf, S. K., Yuniarti, E., & Soon, L. K. (2006). Prediction of energy savings with anidolic integrated ceiling across different daylight climates. *Energy and Buildings, 38*(9), 1120-1129. doi: DOI: 10.1016/j.enbuild.2006.01.005

Wong, S. L., Wan, K. K. W., & Lam, T. N. T. (2010). Artificial neural networks for energy analysis of office buildings with daylighting. In 14 (Ed.), *Applied Energy* (Vol. 87, pp. 551-557).

Yang, I.-H., & Nam, E.-J. (2010). Economic analysis of the daylight-linked lighting control system in office buildings. In 13 (Ed.), *Solar Energy* (Vol. 84, pp. 1513-1525).

Zain-Ahmed, A., Sayigh, A. A. M., Surendran, P. N., Othman, M. Y. H., & Sopian, K. (2000). The Development of Daylighting Design Tools for a Hot, Humid Region. In A. A. M. Sayigh (Ed.), *World Renewable Energy Congress VI* (pp. 578-581). Oxford: Pergamon.

Zain-Ahmed, A., Sopian, K., Othman, M. Y. H., Sayigh, A. A. M., & Surendran, P. N. (2002). Daylighting as a passive solar design strategy in tropical buildings: a case study of Malaysia. *Energy Conversion and Management, 43*(13), 1725-1736. doi: Doi: 10.1016/s0196-8904(01)00007-3

Zain-Ahmed, A., Sopian, K., Zainol Abidin, Z., & Othman, M. Y. H. (2002). The availability of daylight from tropical skies--a case study of Malaysia. *Renewable Energy, 25*(1), 21-30. doi: Doi: 10.1016/s0960-1481(00)00209-3

Appendix A: Simulation Data

Blacksburg_Fixed Light Shelf_Best Annual_South

R0-H6-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Blacksburg_Seasonally Adjustable_Winter_South									
R15-H9-D8	R15-H9-D4	R15-H7-D2	R15-H9-D6	R15-H8-D2	R15-H9-D2	R0-H8-D2	R15-H6-D2	R0-H7-D2	R30-H6-D2
Blacksburg_Seasonally Adjustable_Spring_South									
R0-H6-D8	R15-H9-D8	R15-H7-D8	R0-H7-D8	R15-H9-D6	R15-H8-D6	R0-H7-D6	R15-H8-D8	R15-H7-D6	R15-H8-D4
Blacksburg_Seasonally Adjustable_Summer_South									
R0-H6-D6	R0-H6-D8	R15-H7-D8	R15-H6-D8	R0-H7-D6	R15-H8-D8	R0-H7-D8	R15-H7-D6	R15-H9-D8	R15-H8-D6
Blacksburg_Seasonally Adjustable_Fall_South									
R0-H6-D8	R0-H7-D8	R0-H7-D6	R0-H8-D6	R15-H9-D6	R15-H9-D8	R0-H9-D4	R0-H6-D6	R15-H8-D8	R0-H8-D4

Blacksburg_Fixed Light Shelf_Best Annual_East

R15-H9-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Blacksburg_Seasonally Adjustable_Winter_East									
R15-H6-D8	R0-H6-D6	R0-H9-D2	R15-H8-D2	R0-H8-D4	R15-H8-D8	R15-H7-D8	R15-H7-D2	R15-H9-D2	R45-H7-D2
Blacksburg_Seasonally Adjustable_Spring_East									
R15-H8-D8	R15-H9-D4	R15-H8-D4	R15-H9-D8	R15-H8-D6	R0-H7-D2	R15-H9-D6	R30-H7-D4	R30-H8-D4	R30-H6-D2
Blacksburg_Seasonally Adjustable_Summer_East									
R15-H9-D8	R15-H8-D6	R15-H8-D4	R0-H7-D8	R15-H8-D8	R0-H6-D8	R15-H9-D6	R15-H6-D2	R0-H8-D6	R0-H9-D4
Blacksburg_Seasonally Adjustable_Fall_East									
R0-H7-D2	R30-H7-D4	R15-H9-D4	R15-H8-D4	R15-H9-D8	R15-H6-D2	R15-H9-D6	R30-H7-D6	R15-H8-D6	R30-H9-D8

Blacksburg_Fixed Light Shelf_Best Annual_North

R15-H7-D2

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Blacksburg_Seasonally Adjustable_Winter_North									
R30-H9-D2	R15-H9-D2	R30-H7-D2	R30-H8-D2	R15-H8-D2	R45-H9-D2	R45-H8-D2	R30-H9-D4	R45-H6-D2	R45-H7-D2
Blacksburg_Seasonally Adjustable_Spring_North									
R15-H7-D2	R15-H8-D2	R15-H9-D2	R30-H7-D2	R30-H6-D2	R30-H9-D2	R0-H8-D2	R30-H8-D2	R0-H9-D2	R15-H9-D4
Blacksburg_Seasonally Adjustable_Summer_North									
R15-H8-D2	R15-H8-D4	R15-H7-D4	R15-H9-D4	R15-H7-D2	R15-H9-D2	R15-H7-D6	R0-H7-D2	R15-H6-D2	R0-H9-D2
Blacksburg_Seasonally Adjustable_Fall_North									
R15-H7-D2	R15-H8-D2	R15-H9-D2	R15-H9-D4	R0-H9-D2	R30-H8-D2	R30-H9-D2	R30-H6-D2	R0-H7-D2	R30-H7-D2

Blacksburg_Fixed Light Shelf_Best Annual_West

R0-H7-D2

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Blacksburg_Seasonally Adjustable_Winter_West									
R30-H7-D4	R30-H6-D2	R15-H8-D2	R30-H9-D4	R45-H7-D2	R0-H9-D2	R30-H9-D2	R30-H7-D2	R0-H8-D2	R15-H9-D2
Blacksburg_Seasonally Adjustable_Spring_West									
R30-H7-D8	R30-H8-D6	R30-H7-D6	R30-H6-D8	R30-H9-D8	R30-H7-D4	R15-H9-D6	R30-H6-D4	R30-H9-D6	R15-H9-D8
Blacksburg_Seasonally Adjustable_Summer_West									
R15-H9-D8	R15-H9-D6	R15-H6-D4	R15-H6-D6	R15-H8-D4	R15-H7-D6	R15-H8-D6	R15-H7-D4	R0-H9-D4	R15-H6-D8
Blacksburg_Seasonally Adjustable_Fall_West									
R15-H9-D6	R15-H8-D4	R15-H9-D8	R15-H7-D8	R30-H7-D8	R15-H9-D2	R15-H6-D6	R15-H8-D6	R30-H7-D6	R15-H8-D8

Fig. A.1 Best fixed and seasonally adjustable light shelves for Blacksburg, VA.

Blacksburg_Best Fixed_South			Winter	Spring	Summer	Fall			
R0-H6-D8			R15-H9-D8	R0-H6-D8	R0-H6-D6	R0-H6-D8	Blacksburg_Best Adjustable_South		
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Blacksburg_Seasonally Adjustable_Segmented_Winter_South									
RP15-RS15-DP3-DS4-H9	RP15-RS15-DP2-DS4-H9	RP15-RS15-DP4-DS4-H9	RP30-RS15-DP1-DS4-H9	RP15-RS15-DP1-DS4-H9	RP0-RS15-DP2-DS4-H9	RP0-RS15-DP1-DS4-H9	RP15-RS0-DP2-DS2-H9	RP30-RS0-DP2-DS2-H9	RP15-RS0-DP1-DS2-H9
Blacksburg_Seasonally Adjustable_Segmented_Spring_South									
RP0-RS0-DP4-DS4-H6	RP0-RS15-DP4-DS4-H7	RP0-RS15-DP4-DS4-H8	RP15-RS15-DP4-DS3-H9	RP0-RS15-DP3-DS4-H7	RP15-RS15-DP3-DS4-H9	RP0-RS15-DP4-DS3-H8	RP15-RS0-DP2-DS3-H8	RP15-RS15-DP4-DS4-H9	RP0-RS15-DP4-DS3-H7
Blacksburg_Seasonally Adjustable_Segmented_Summer_South									
RP0-RS0-DP3-DS3-H6	RP15-RS0-DP3-DS4-H6	RP0-RS15-DP4-DS3-H7	RP15-RS0-DP3-DS3-H6	RP0-RS0-DP2-DS3-H6	RP15-RS0-DP2-DS4-H6	RP15-RS0-DP4-DS4-H6	RP15-RS0-DP4-DS3-H6	RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS3-H6
Blacksburg_Seasonally Adjustable_Segmented_Fall_South									
RP0-RS0-DP4-DS4-H6	RP0-RS0-DP3-DS4-H6	RP0-RS0-DP1-DS3-H7	RP0-RS0-DP1-DS4-H7	RP15-RS0-DP1-DS4-H7	RP0-RS0-DP4-DS3-H6	RP0-RS15-DP4-DS4-H6	RP0-RS0-DP3-DS3-H6	RP45-RS0-DP1-DS4-H7	RP30-RS0-DP1-DS4-H7

Fig. A.2 Best segmented light shelf for south orientation, Blacksburg, VA

Miami_Best Fixed_South			Winter	Spring	Summer	Fall			
R0-H6-D8			R0-H7-D8	R0-H6-D8	R15-H6-D8	R0-H6-D8	Miami_Best Adjustable_South		
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Miami_Seasonally Adjustable_Segmented_Winter_South									
RP15-RS0-DP4-DS4-H8	RP0-RS0-DP3-DS4-H8	RP0-RS0-DP2-DS4-H8	RP0-RS0-DP4-DS4-H7	RP0-RS0-DP3-DS4-H7	RP15-RS0-DP3-DS4-H8	RP0-RS0-DP3-DS4-H6	RP0-RS0-DP4-DS3-H7	RP0-RS0-DP4-DS4-H6	RP0-RS15-DP4-DS4-H9
Miami_Seasonally Adjustable_Segmented_Spring_South									
RP0-RS0-DP4-DS4-H6	RP0-RS0-DP3-DS4-H6	RP15-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP15-RS0-DP4-DS4-H7	RP0-RS15-DP4-DS4-H7	RP15-RS0-DP3-DS4-H7	RP0-RS0-DP3-DS3-H7	RP15-RS0-DP3-DS4-H6
Miami_Seasonally Adjustable_Segmented_Summer_South									
RP15-RS15-DP4-DS4-H6	RP15-RS0-DP4-DS2-H7	RP15-RS15-DP4-DS3-H7	RP15-RS0-DP3-DS3-H6	RP30-RS0-DP3-DS3-H6	RP0-RS15-DP4-DS3-H6	RP30-RS0-DP4-DS3-H6	RP30-RS15-DP4-DS4-H6	RP0-RS15-DP3-DS2-H7	RP15-RS15-DP3-DS4-H6
Miami_Seasonally Adjustable_Segmented_Fall_South									
RP0-RS0-DP3-DS4-H6	RP0-RS0-DP4-DS4-H6	RP15-RS0-DP4-DS4-H6	RP0-RS15-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP15-RS0-DP3-DS4-H6	RP15-RS0-DP4-DS4-H7	RP0-RS15-DP3-DS4-H7	RP0-RS0-DP4-DS3-H7	RP0-RS0-DP3-DS3-H6

Fig. A.3 Best segmented light shelf for south orientation, Miami, FL

Boston_Best Fixed_South			Winter	Spring	Summer	Fall			
R0-H6-D8			R0-H6-D8	R0-H6-D8	R0-H6-D8	R0-H6-D8	Boston_Best Adjustable_South		
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Boston_Seasonally Adjustable_Segmented_Winter_South									
RP15-RS0-DP1-DS3-H9	RP0-RS0-DP1-DS4-H7	RP0-RS0-DP4-DS4-H6	RP15-RS0-DP2-DS3-H9	RP0-RS0-DP1-DS3-H8	RP0-RS0-DP1-DS3-H7	RP0-RS30-DP4-DS3-H8	RP30-RS0-DP1-DS3-H9	RP45-RS0-DP2-DS4-H6	RP30-RS0-DP1-DS4-H6
Boston_Seasonally Adjustable_Segmented_Spring_South									
RP0-RS0-DP4-DS4-H6	RP15-RS0-DP4-DS3-H8	RP0-RS0-DP2-DS3-H7	RP15-RS0-DP3-DS3-H7	RP15-RS0-DP3-DS4-H7	RP0-RS15-DP3-DS4-H8	RP15-RS0-DP4-DS3-H7	RP0-RS15-DP2-DS4-H8	RP0-RS0-DP4-DS3-H6	RP15-RS0-DP4-DS4-H7
Boston_Seasonally Adjustable_Segmented_Summer_South									
RP15-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS3-H6	RP0-RS15-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP0-RS0-DP3-DS3-H6	RP0-RS0-DP3-DS4-H6	RP0-RS15-DP4-DS4-H6	RP0-RS15-DP4-DS3-H7	RP15-RS0-DP3-DS4-H6
Boston_Seasonally Adjustable_Segmented_Fall_South									
RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H7	RP0-RS0-DP3-DS4-H7	RP0-RS0-DP2-DS4-H7	RP0-RS0-DP4-DS3-H8	RP0-RS0-DP3-DS4-H6	RP15-RS0-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP15-RS0-DP4-DS4-H8	RP0-RS0-DP3-DS3-H7

Fig. A.4 Best segmented light shelf for south orientation, Boston, MA

Miami_Fixed Light Shelf_Best Annual_South
R0-H6-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Miami_Seasonally Adjustable_Winter_South									
R0-H7-D8	R0-H6-D8	R0-H8-D8	R0-H7-D6	R15-H9-D8	R15-H9-D6	R0-H9-D4	R0-H8-D6	R15-H8-D8	R0-H8-D4
Miami_Seasonally Adjustable_Spring_South									
R0-H6-D8	R0-H7-D8	R0-H7-D6	R15-H8-D8	R0-H6-D6	R15-H8-D6	R15-H7-D8	R15-H9-D8	R15-H9-D6	R0-H8-D4
Miami_Seasonally Adjustable_Summer_South									
R15-H6-D8	R15-H7-D8	R15-H6-D6	R0-H6-D6	R15-H7-D6	R0-H7-D4	R15-H8-D8	R0-H6-D4	R15-H8-D4	R0-H7-D6
Miami_Seasonally Adjustable_Fall_South									
R0-H6-D8	R0-H6-D6	R0-H7-D6	R0-H7-D8	R15-H8-D8	R15-H7-D8	R15-H8-D6	R15-H9-D6	R15-H9-D8	R15-H6-D8

Miami_Fixed Light Shelf_Best Annual_East
R45-H6-D6

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Miami_Seasonally Adjustable_Winter_East									
R0-H6-D6	R15-H6-D8	R15-H7-D8	R15-H8-D8	R15-H8-D4	R15-H9-D6	R15-H9-D8	R15-H7-D6	R15-H8-D6	R30-H7-D4
Miami_Seasonally Adjustable_Spring_East									
R15-H9-D8	R15-H9-D6	R0-H6-D8	R15-H8-D8	R15-H8-D4	R0-H9-D4	R0-H9-D8	R0-H6-D2	R0-H6-D4	R15-H8-D6
Miami_Seasonally Adjustable_Summer_East									
R15-H8-D8	R15-H9-D8	R15-H9-D6	R15-H9-D4	R0-H6-D8	R15-H7-D2	R0-H8-D4	R15-H8-D6	R15-H8-D4	R0-H7-D8
Miami_Seasonally Adjustable_Fall_East									
R15-H9-D8	R15-H8-D8	R0-H6-D8	R0-H8-D4	R15-H8-D4	R15-H8-D6	R15-H6-D2	R15-H7-D4	R0-H6-D2	R15-H6-D4

Miami_Fixed Light Shelf_Best Annual_North
R0-H8-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Miami_Seasonally Adjustable_Winter_North									
R15-H7-D2	R15-H9-D2	R30-H7-D2	R15-H8-D2	R30-H6-D2	R30-H9-D2	R0-H8-D2	R30-H8-D2	R30-H8-D4	R15-H9-D4
Miami_Seasonally Adjustable_Spring_North									
R15-H8-D2	R15-H8-D4	R15-H7-D2	R15-H9-D2	R15-H7-D4	R15-H6-D2	R0-H7-D2	R0-H9-D2	R15-H9-D4	R15-H6-D4
Miami_Seasonally Adjustable_Summer_North									
R15-H8-D4	R15-H7-D4	R15-H6-D4	R15-H7-D6	R15-H6-D6	R15-H7-D8	R15-H8-D8	R15-H8-D6	R15-H6-D8	R15-H9-D4
Miami_Seasonally Adjustable_Fall_North									
R15-H8-D2	R15-H7-D2	R15-H8-D4	R15-H9-D4	R0-H7-D2	R0-H8-D2	R15-H7-D4	R15-H6-D2	R30-H7-D4	R15-H8-D6

Miami_Fixed Light Shelf_Best Annual_West
R15-H6-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Miami_Seasonally Adjustable_Winter_West									
R15-H8-D8	R15-H7-D6	R15-H7-D8	R15-H6-D4	R0-H8-D4	R15-H6-D6	R15-H6-D8	R15-H9-D6	R0-H6-D2	R15-H7-D4
Miami_Seasonally Adjustable_Spring_West									
R0-H6-D8	R15-H6-D6	R15-H6-D8	R15-H7-D4	R15-H7-D6	R15-H7-D8	R15-H6-D4	R15-H8-D4	R0-H6-D4	R0-H6-D2
Miami_Seasonally Adjustable_Summer_West									
R15-H9-D8	R15-H9-D6	R15-H8-D8	R15-H6-D8	R0-H6-D8	R15-H7-D8	R15-H8-D4	R15-H6-D6	R15-H7-D6	R15-H6-D4
Miami_Seasonally Adjustable_Fall_West									
R0-H6-D8	R15-H9-D8	R15-H8-D8	R0-H7-D8	R15-H6-D6	R15-H9-D6	R0-H8-D4	R15-H7-D4	R15-H8-D4	R15-H7-D8

Fig. A.5 Best fixed and seasonally adjustable light shelves for 4-orientations in Miami, FL

Boston_Fixed Light Shelf_Best Annual_South

R0-H6-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Boston_Seasonally Adjustable_Winter_South									
R0-H6-D8	R30-H8-D2	R0-H8-D2	R0-H9-D6	R0-H9-D2	R15-H9-D4	R30-H8-D4	R45-H9-D2	R15-H6-D2	R30-H6-D2
Boston_Seasonally Adjustable_Spring_South									
R0-H6-D8	R0-H7-D8	R0-H7-D6	R15-H8-D8	R0-H7-D4	R0-H8-D6	R0-H8-D4	R0-H6-D6	R15-H9-D8	R15-H7-D8
Boston_Seasonally Adjustable_Summer_South									
R0-H6-D8	R0-H6-D6	R0-H7-D8	R0-H7-D6	R15-H7-D8	R15-H6-D8	R15-H8-D8	R0-H7-D4	R15-H8-D6	R0-H8-D6
Boston_Seasonally Adjustable_Fall_South									
R0-H6-D8	R0-H7-D8	R0-H7-D6	R0-H8-D8	R0-H7-D4	R0-H8-D6	R0-H9-D6	R0-H6-D6	R0-H8-D4	R15-H9-D6

Boston_Fixed Light Shelf_Best Annual_East

R15-H8-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Boston_Seasonally Adjustable_Winter_East									
R15-H8-D2	R15-H7-D2	R15-H9-D2	R0-H9-D2	R0-H8-D2	R30-H8-D2	R30-H7-D2	R15-H6-D8	R30-H9-D4	R30-H9-D2
Boston_Seasonally Adjustable_Spring_East									
R0-H6-D8	R0-H6-D6	R0-H7-D6	R15-H8-D8	R15-H9-D6	R15-H9-D8	R15-H7-D8	R15-H8-D6	R15-H6-D8	R30-H9-D8
Boston_Seasonally Adjustable_Summer_East									
R15-H8-D8	R15-H6-D8	R15-H8-D6	R15-H9-D8	R15-H8-D4	R0-H6-D8	R15-H6-D2	R15-H9-D6	R0-H6-D6	R0-H7-D8
Miami_Seasonally Adjustable_Fall_East									
R15-H9-D8	R15-H9-D6	R0-H6-D8	R0-H6-D6	R15-H8-D6	R15-H7-D2	R15-H7-D8	R30-H6-D4	R15-H6-D8	R30-H7-D6

Boston_Fixed Light Shelf_Best Annual_North

R15-H8-D2

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Boston_Seasonally Adjustable_Winter_North									
R30-H9-D2	R15-H9-D2	R30-H8-D2	R45-H9-D2	R45-H6-D2	R30-H7-D2	R45-H8-D2	R45-H7-D2	R15-H8-D2	R30-H9-D4
Boston_Seasonally Adjustable_Spring_North									
R15-H7-D2	R15-H9-D2	R15-H8-D2	R30-H7-D2	R30-H6-D2	R30-H9-D2	R30-H8-D2	R0-H7-D2	R0-H8-D2	R15-H9-D4
Boston_Seasonally Adjustable_Summer_North									
R15-H8-D2	R15-H7-D4	R15-H8-D4	R15-H9-D4	R15-H7-D2	R15-H6-D2	R15-H8-D6	R15-H9-D2	R15-H7-D6	R0-H7-D2
Miami_Seasonally Adjustable_Fall_North									
R15-H7-D2	R15-H9-D2	R15-H8-D2	R30-H7-D2	R15-H9-D4	R30-H8-D2	R30-H9-D2	R30-H6-D2	R0-H9-D2	R0-H7-D2

Boston_Fixed Light Shelf_Best Annual_West

R15-H9-D8

Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Boston_Seasonally Adjustable_Winter_West									
R0-H7-D2	R15-H7-D2	R30-H8-D4	R30-H7-D4	R45-H7-D2	R30-H7-D2	R15-H8-D2	R0-H8-D2	R45-H8-D2	R15-H9-D2
Boston_Seasonally Adjustable_Spring_West									
R15-H9-D6	R15-H8-D6	R15-H6-D6	R15-H8-D8	R15-H7-D8	R15-H6-D8	R15-H8-D4	R15-H6-D4	R15-H7-D4	R15-H6-D2
Boston_Seasonally Adjustable_Summer_West									
R0-H6-D8	R15-H9-D8	R15-H7-D6	R15-H7-D4	R15-H7-D8	R15-H9-D6	R15-H6-D4	R15-H6-D6	R15-H6-D8	R15-H6-D2
Miami_Seasonally Adjustable_Fall_West									
R15-H8-D8	R15-H7-D8	R15-H9-D6	R15-H8-D6	R15-H7-D6	R15-H7-D4	R15-H6-D4	R15-H9-D8	R15-H6-D8	R15-H6-D6

Fig. A.6 Best fixed and seasonally adjustable light shelves for 4-orientations in Miami, FL

Best Segmented for Winter, South in Boston, MA

RP15-RS0-DP1-DS3-H9	RP0-RS0-DP1-DS4-H7	RP0-RS0-DP4-DS4-H6	RP15-RS0-DP2-DS3-H9	RP0-RS0-DP1-DS3-H8	RP0-RS0-DP1-DS3-H7	RP0-RS30-DP4-DS3-H8	RP30-RS0-DP1-DS3-H9	RP45-RS0-DP2-DS4-H6	RP30-RS0-DP1-DS4-H6		RP15-RS0-DP1-DS3-H9	RP0-RS0-DP4-DS4-H6
3	4	13	8	7	4	6	4	5	3	Under-lit	3	13
37	34	33	33	32	32	31	31	31	31	Well-lit	37	33
60	62	54	59	60	64	63	64	64	66	Over-lit	60	54
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Spring, South, Boston, MA

RP0-RS0-DP4-DS4-H6	RP15-RS0-DP4-DS3-H8	RP0-RS0-DP2-DS3-H7	RP15-RS0-DP3-DS3-H7	RP15-RS0-DP3-DS4-H7	RP0-RS15-DP3-DS4-H8	RP15-RS0-DP4-DS3-H7	RP0-RS15-DP2-DS4-H8	RP0-RS0-DP4-DS3-H6	RP15-RS0-DP4-DS4-H7		RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6
10	4	2	2	2	2	3	2	7	4	Under-lit	10	10
68	63	63	63	63	63	62	62	61	61	Well-lit	68	68
22	33	35	35	35	36	35	36	31	35	Over-lit	22	22
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Summer, South, Boston, MA

RP15-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS3-H6	RP0-RS15-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP0-RS0-DP3-DS3-H6	RP0-RS0-DP3-DS4-H6	RP0-RS15-DP4-DS4-H6	RP0-RS15-DP4-DS3-H7	RP15-RS0-DP3-DS4-H6		RP15-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6
1	2	2	2	2	2	5	0	0	2	Under-lit	1	2
96	95	95	95	93	93	93	93	93	92	Well-lit	96	95
3	2	3	3	4	4	2	7	7	6	Over-lit	3	2
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Fall, South, Boston, MA

RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H7	RP0-RS0-DP3-DS4-H7	RP0-RS0-DP2-DS4-H7	RP0-RS0-DP4-DS3-H8	RP0-RS0-DP3-DS4-H6	RP15-RS0-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP15-RS0-DP4-DS4-H8	RP0-RS0-DP3-DS3-H7		RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6
0	2	3	0	6	1	0	0	2	1	Under-lit	0	0
75	73	70	69	68	67	65	64	64	64	Well-lit	75	75
25	25	26	31	26	32	35	36	34	36	Over-lit	25	25
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Fig. A.7 Data for adjustable segmented light shelf for Boston, MA

Best Segmented for Winter, South in Blacksburg, VA

RP15-RS15-DP3-DS4-H9	RP15-RS15-DP2-DS4-H9	RP15-RS15-DP4-DS4-H9	RP30-RS15-DP1-DS4-H9	RP15-RS15-DP1-DS4-H9	RP0-RS15-DP2-DS4-H9	RP0-RS15-DP1-DS4-H9	RP15-RS0-DP2-DS2-H9	RP30-RS0-DP2-DS2-H9	RP15-RS0-DP1-DS2-H9		RP15-RS15-DP3-DS4-H9	RP15-RS15-DP4-DS4-H9
7	7	12	7	9	14	10	10	10	11	Under-lit	7	12
50	46	45	45	44	43	43	43	43	42	Well-lit	50	45
43	47	43	49	47	43	47	47	47	47	Over-lit	43	43
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Spring, South, Blacksburg, VA

RP0-RS0-DP4-DS4-H6	RP0-RS15-DP4-DS4-H7	RP0-RS15-DP4-DS4-H8	RP15-RS15-DP4-DS3-H9	RP0-RS15-DP3-DS4-H7	RP15-RS15-DP3-DS4-H9	RP0-RS15-DP4-DS3-H8	RP15-RS0-DP2-DS3-H8	RP15-RS15-DP4-DS4-H9	RP0-RS15-DP4-DS3-H7		RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6
14	5	5	4	3	2	7	7	6	2	Under-lit	14	14
75	72	71	69	69	69	68	68	68	68	Well-lit	75	75
11	23	24	27	28	29	25	26	26	30	Over-lit	11	11
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Summer, South, Blacksburg, VA

RP0-RS0-DP3-DS3-H6	RP15-RS0-DP3-DS4-H6	RP0-RS15-DP4-DS3-H7	RP15-RS0-DP3-DS3-H6	RP0-RS0-DP2-DS3-H6	RP15-RS0-DP2-DS4-H6	RP15-RS0-DP4-DS4-H6	RP15-RS0-DP4-DS3-H6	RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS3-H6		RP0-RS0-DP3-DS3-H6	RP0-RS0-DP3-DS3-H6
2	3	2	1	4	4	4	2	6	5	Under-lit	2	2
96	95	95	95	94	94	94	94	93	93	Well-lit	96	96
2	2	3	4	2	2	2	4	1	2	Over-lit	2	2
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Fall, South, Blacksburg, VA

RP0-RS0-DP4-DS4-H6	RP0-RS0-DP3-DS4-H6	RP0-RS0-DP1-DS3-H7	RP0-RS0-DP1-DS4-H7	RP15-RS0-DP1-DS4-H7	RP0-RS0-DP4-DS3-H6	RP0-RS15-DP4-DS4-H6	RP0-RS0-DP3-DS3-H6	RP45-RS0-DP1-DS4-H7	RP30-RS0-DP1-DS4-H7		RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6
0	2	2	2	1	1	0	1	1	2	Under-lit	0	0
76	65	62	62	62	61	61	60	60	60	Well-lit	76	76
24	32	36	36	37	38	39	39	39	39	Over-lit	24	24
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Fig. A.8 Data for adjustable segmented light shelf for Blacksburg, VA

Best Segmented for Winter, South in Miami, MA

RP15-RS0-DP1-DS3-H9	RP0-RS0-DP1-DS4-H7	RP0-RS0-DP4-DS4-H6	RP15-RS0-DP2-DS3-H9	RP0-RS0-DP1-DS3-H8	RP0-RS0-DP1-DS3-H7	RP0-RS30-DP4-DS3-H8	RP30-RS0-DP1-DS3-H9	RP45-RS0-DP2-DS4-H6	RP30-RS0-DP1-DS4-H6		RP15-RS0-DP4-DS4-H8	RP0-RS0-DP4-DS4-H7
3	4	13	8	7	4	6	4	5	3	Under-lit	2	2
37	34	33	33	32	32	31	31	31	31	Well-lit	73	71
60	62	54	59	60	64	63	64	64	66	Over-lit	26	27
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Spring, South, Miami, MA

RP0-RS0-DP4-DS4-H6	RP15-RS0-DP4-DS3-H8	RP0-RS0-DP2-DS3-H7	RP15-RS0-DP3-DS3-H7	RP15-RS0-DP3-DS4-H7	RP0-RS15-DP3-DS4-H8	RP15-RS0-DP4-DS3-H7	RP0-RS15-DP2-DS4-H8	RP0-RS0-DP4-DS3-H6	RP15-RS0-DP4-DS4-H7		RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6
10	4	2	2	2	2	3	2	7	4	Under-lit	2	2
68	63	63	63	63	63	62	62	61	61	Well-lit	95	95
22	33	35	35	35	36	35	36	31	35	Over-lit	2	2
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Summer, South, Miami, MA

RP15-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS3-H6	RP0-RS15-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP0-RS0-DP3-DS3-H6	RP0-RS0-DP3-DS4-H6	RP0-RS15-DP4-DS4-H6	RP0-RS15-DP4-DS3-H7	RP15-RS0-DP3-DS4-H6		RP15-RS15-DP4-DS4-H6	RP15-RS15-DP4-DS4-H6
1	2	2	2	2	2	5	0	0	2	Under-lit	3	3
96	95	95	95	93	93	93	93	93	92	Well-lit	97	97
3	2	3	3	4	4	2	7	7	6	Over-lit	0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Best Segmented for Fall, South, Miami, MA

RP0-RS0-DP4-DS4-H6	RP0-RS0-DP4-DS4-H7	RP0-RS0-DP3-DS4-H7	RP0-RS0-DP2-DS4-H7	RP0-RS0-DP4-DS3-H8	RP0-RS0-DP3-DS4-H6	RP15-RS0-DP4-DS4-H7	RP0-RS0-DP2-DS4-H6	RP15-RS0-DP4-DS4-H8	RP0-RS0-DP3-DS3-H7		RP0-RS0-DP3-DS4-H6	RP0-RS0-DP4-DS4-H6
0	2	3	0	6	1	0	0	2	1	Under-lit	4	3
75	73	70	69	68	67	65	64	64	64	Well-lit	94	94
25	25	26	31	26	32	35	36	34	36	Over-lit	2	2
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Seg.	Best Simp.

Fig. A.9 Data for adjustable segmented light shelf for Miami, FL

Boston_Fixed Light Shelf_Best Annual_South

R0-H6-D8	R0-H7-D8	R0-H7-D4	R0-H7-D6	R15-H9-D8	R15-H9-D6	R0-H8-D4	R15-H6-D8	R15-H9-D4	R15-H6-D4		R0-H6-D8	R0-H7-D0
5	9	3	6	3	4	7	0	2	1	Under-lit	5	1
54	42	39	38	38	37	35	35	34	34	Well-lit	54	26
41	49	58	56	59	59	59	65	64	65	Over-lit	41	73
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Boston_Fixed Light Shelf_Best Annual_East

R15-H8-D8	R15-H9-D6	R15-H9-D4	R0-H6-D8	R15-H9-D8	R0-H7-D6	R15-H7-D8	R30-H9-D8	R0-H6-D6	R15-H6-D2		R15-H8-D8	R0-H7-D0
37	37	31	53	40	46	37	35	43	32	Under-lit	37	26
46	46	46	45	44	42	42	42	41	41	Well-lit	46	38
17	17	22	2	17	12	21	23	16	26	Over-lit	17	36
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Boston_Fixed Light Shelf_Best Annual_North

R15-H8-D2	R15-H7-D2	R15-H9-D2	R30-H7-D2	R0-H8-D2	R30-H9-D2	R30-H6-D2	R30-H8-D4	R30-H8-D2	R0-H7-D2		R15-H8-D2	R0-H7-D0
32	32	32	33	35	35	35	36	36	36	Under-lit	32	31
68	68	68	67	65	65	65	64	64	64	Well-lit	68	62
0	0	0	0	0	0	0	0	0	0	Over-lit	0	7
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Boston_Fixed Light Shelf_Best Annual_West

R15-H9-D8	R15-H7-D8	R15-H6-D2	R15-H9-D6	R15-H8-D4	R0-H9-D4	R15-H7-D6	R15-H6-D6	R15-H6-D8	R15-H8-D6		R15-H9-D8	R0-H7-D0
25	19	17	23	17	34	21	20	20	20	Under-lit	25	16
31	31	29	28	28	26	26	26	26	26	Well-lit	31	21
45	50	55	49	55	40	53	54	54	54	Over-lit	45	63
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Fig. A.10 Data for annually optimized fixed light shelf for Boston, MA

Boston_Seasonally Adjustable_Winter_South

R0-H6-D8	R30-H8-D2	R0-H8-D2	R0-H9-D6	R0-H9-D2	R15-H9-D4	R30-H8-D4	R45-H9-D2	R15-H6-D2	R30-H6-D2		R0-H6-D8	R0-H6-D8
13	3	3	20	3	2	7	5	3	2	Under-lit	13	13
33	30	29	28	27	27	26	26	26	26	Well-lit	33	33
54	67	68	52	69	71	67	69	70	71	Over-lit	54	54
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Winter_East

R15-H8-D2	R15-H7-D2	R15-H9-D2	R0-H9-D2	R0-H8-D2	R30-H8-D2	R30-H7-D2	R15-H6-D8	R30-H9-D4	R30-H9-D2		R15-H8-D2	R15-H8-D8
36	37	38	41	39	38	40	46	40	39	Under-lit	36	51
42	41	40	40	40	40	39	38	38	38	Well-lit	42	35
21	21	21	19	21	22	21	16	21	23	Over-lit	21	14
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Winter_North

R30-H9-D2	R15-H9-D2	R30-H8-D2	R45-H9-D2	R45-H6-D2	R30-H7-D2	R45-H8-D2	R45-H7-D2	R15-H8-D2	R30-H9-D4		R30-H9-D2	R15-H8-D2
43	43	45	45	45	46	46	46	47	47	Under-lit	43	47
57	57	55	55	55	54	54	54	53	53	Well-lit	57	53
0	0	0	0	0	0	0	0	0	0	Over-lit	0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Winter_West

R0-H7-D2	R15-H7-D2	R30-H8-D4	R30-H7-D4	R45-H7-D2	R30-H7-D2	R15-H8-D2	R0-H8-D2	R45-H8-D2	R15-H9-D2		R0-H7-D2	R15-H9-D8
27	26	29	30	29	28	27	30	30	29	Under-lit	27	41
33	32	31	31	31	31	31	30	30	29	Well-lit	33	20
40	42	40	40	40	41	42	40	40	42	Over-lit	40	39
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.11 Data for seasonally optimized adjustable light shelf for Winter, Boston, MA

Boston_Seasonally Adjustable_Spring_South

R0-H6-D8	R0-H7-D8	R0-H7-D6	R15-H8-D8	R0-H7-D4	R0-H8-D6	R0-H8-D4	R0-H6-D6	R15-H9-D8	R15-H7-D8		R0-H6-D8	R0-H6-D8
10	14	6	3	2	12	6	5	3	2	Under-lit	10	10
68	60	60	60	58	57	57	56	55	55	Well-lit	68	68
22	26	34	36	40	31	37	39	41	43	Over-lit	22	22
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Spring_East

R0-H6-D8	R0-H6-D6	R0-H7-D6	R15-H8-D8	R15-H9-D6	R15-H9-D8	R15-H7-D8	R15-H8-D6	R15-H6-D8	R30-H9-D8		R0-H6-D8	R15-H8-D8
51	40	45	36	37	38	36	35	36	35	Under-lit	51	36
48	48	46	46	45	45	45	44	41	41	Well-lit	48	46
1	12	9	17	17	17	19	21	23	24	Over-lit	1	17
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Spring_North

R15-H7-D2	R15-H9-D2	R15-H8-D2	R30-H7-D2	R30-H6-D2	R30-H9-D2	R30-H8-D2	R0-H7-D2	R0-H8-D2	R15-H9-D4		R15-H7-D2	R15-H8-D2
31	31	32	32	33	33	33	33	35	35	Under-lit	31	32
69	69	68	68	67	67	67	67	65	65	Well-lit	69	68
0	0	0	0	0	0	0	0	0	0	Over-lit	0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Spring_West

R15-H9-D6	R15-H8-D6	R15-H6-D6	R15-H8-D8	R15-H7-D8	R15-H6-D8	R15-H8-D4	R15-H6-D4	R15-H7-D4	R15-H6-D2		R15-H9-D6	R15-H9-D8
15	14	13	17	16	15	13	15	16	14	Under-lit	15	23
33	32	32	31	31	31	31	31	30	30	Well-lit	33	28
52	54	55	51	53	54	55	55	55	56	Over-lit	52	49
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.12 Data for seasonally optimized adjustable light shelf for Spring, Boston, MA

Boston_Seasonally Adjustable_Summer_South

R0-H6-D8	R0-H6-D6	R0-H7-D8	R0-H7-D6	R15-H7-D8	R15-H6-D8	R15-H8-D8	R0-H7-D4	R15-H8-D6	R0-H8-D6		R0-H6-D8	R0-H6-D8
2	2	7	4	1	0	1	2	1	11	Under-lit	2	2
95	93	90	87	86	86	84	79	79	79	Well-lit	95	95
2	4	3	9	13	14	15	19	20	11	Over-lit	2	2
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Summer_East

R15-H8-D8	R15-H6-D8	R15-H8-D6	R15-H9-D8	R15-H8-D4	R0-H6-D8	R15-H6-D2	R15-H9-D6	R0-H6-D6	R0-H7-D8		R15-H8-D8	R15-H8-D8
17	21	17	20	12	38	11	21	32	40	Under-lit	17	17
67	65	65	64	63	62	62	61	60	60	Well-lit	67	67
17	13	17	17	25	0	27	17	7	0	Over-lit	17	17
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Summer_North

R15-H8-D2	R15-H7-D4	R15-H8-D4	R15-H9-D4	R15-H7-D2	R15-H6-D2	R15-H8-D6	R15-H9-D2	R15-H7-D6	R0-H7-D2		R15-H8-D2	R15-H8-D2
18	21	22	22	22	23	23	18	24	24	Under-lit	18	18
82	79	78	78	78	77	77	77	76	76	Well-lit	82	82
0	0	0	0	0	0	0	5	0	0	Over-lit	0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Summer_West

R0-H6-D8	R15-H9-D8	R15-H7-D6	R15-H7-D4	R15-H7-D8	R15-H9-D6	R15-H6-D4	R15-H6-D6	R15-H6-D8	R15-H6-D2		R0-H6-D8	R15-H9-D8
6	3	1	1	1	0	0	0	0	0	Under-lit	6	3
50	47	47	47	47	47	46	46	46	45	Well-lit	50	47
44	50	52	52	52	53	54	54	54	55	Over-lit	44	50
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.13 Data for seasonally optimized adjustable light shelf for Summer, Boston, MA

Boston_Seasonally Adjustable_Fall_South

R0-H6-D8	R0-H7-D8	R0-H7-D6	R0-H8-D8	R0-H7-D4	R0-H8-D6	R0-H9-D6	R0-H6-D6	R0-H8-D4	R15-H9-D6		R0-H6-D8	R0-H6-D8
0	2	1	11	0	3	8	0	2	0	Under-lit	0	0
75	73	64	63	62	61	57	56	55	55	Well-lit	75	75
25	25	36	26	38	36	35	44	44	45	Over-lit	25	25
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Fall_East

R15-H9-D8	R15-H9-D6	R0-H6-D8	R0-H6-D6	R15-H8-D6	R15-H7-D2	R15-H7-D8	R30-H6-D4	R15-H6-D8	R30-H7-D6		R15-H9-D8	R15-H8-D8
31	30	45	38	29	21	31	30	32	31	Under-lit	31	31
43	43	42	39	39	39	38	38	37	37	Well-lit	43	37
26	27	13	23	32	40	31	32	31	31	Over-lit	26	31
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Fall_North

R15-H7-D2	R15-H9-D2	R15-H8-D2	R30-H7-D2	R15-H9-D4	R30-H8-D2	R30-H9-D2	R30-H6-D2	R0-H9-D2	R0-H7-D2		R15-H7-D2	R15-H8-D2
30	31	31	32	33	33	33	33	34	34	Under-lit	30	31
70	69	69	68	67	67	67	67	66	66	Well-lit	70	69
0	0	0	0	0	0	0	0	0	0	Over-lit	0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Boston_Seasonally Adjustable_Fall_West

R15-H8-D8	R15-H7-D8	R15-H9-D6	R15-H8-D6	R15-H7-D6	R15-H7-D4	R15-H6-D4	R15-H9-D8	R15-H6-D8	R15-H6-D6		R15-H8-D8	R15-H9-D8
9	8	7	7	7	7	5	11	7	8	Under-lit	9	11
39	38	38	38	38	38	38	36	36	35	Well-lit	39	36
52	54	55	55	55	55	57	53	56	57	Over-lit	52	53
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.14 Data for seasonally optimized adjustable light shelf for Fall, Boston, MA

Blacksburg_Fixed Light Shelf_Best Annual_South

R0-H6-D8	R0-H7-D8	R15-H9-D8	R0-H8-D6	R0-H7-D6	R15-H9-D6	R15-H7-D8	R15-H6-D8	R15-H7-D4	R0-H9-D4		R0-H6-D8-F0	No Light Shelf
10	16	6	17	11	6	2	1	1	13		10	2
66	60	56	53	51	50	50	50	50	49		66	39
24	25	38	31	38	44	49	50	50	38		24	60
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Blacksburg_Fixed Light Shelf_Best Annual_East

R15-H9-D8	R0-H7-D2	R0-H7-D8	R15-H7-D2	R0-H9-D4	R15-H9-D6	R15-H9-D4	R30-H8-D4	R30-H6-D2	R15-H8-D8		R15-H9-D8-F90	No Light Shelf
37	26	57	26	42	36	30	30	29	35		37	24
38	36	35	35	34	34	33	32	32	31		38	29
25	38	8	40	24	30	37	38	39	34		25	47
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Blacksburg_Fixed Light Shelf_Best Annual_North

R15-H7-D2	R15-H9-D2	R15-H8-D2	R30-H8-D2	R30-H7-D2	R30-H6-D2	R0-H7-D2	R0-H8-D2	R30-H8-D4	R15-H9-D4		R15-H7-D2-F180	No Light Shelf
31	31	32	33	32	33	35	35	35	36		31	31
69	69	68	67	67	66	65	65	65	64		69	62
0	0	0	0	1	1	0	0	0	0		0	7
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Blacksburg_Fixed Light Shelf_Best Annual_West

R0-H7-D2	R15-H9-D8	R15-H6-D2	R15-H8-D4	R0-H9-D4	R15-H9-D6	R30-H7-D8	R15-H8-D8	R15-H7-D8	R15-H9-D4		R0-H7-D2-F270	No Light Shelf
21	31	22	26	36	32	32	31	28	26		21	18
31	30	29	27	26	26	26	26	26	26		31	26
48	39	49	46	37	41	41	43	45	48		48	56
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Fig. A.15 Data for annually optimized fixed light shelf for Blacksburg, VA

Blacksburg_Seasonally Adjustable_Winter_South

R15-H9-D8	R15-H9-D4	R15-H7-D2	R15-H9-D6	R15-H8-D2	R15-H9-D2	R0-H8-D2	R15-H6-D2	R0-H7-D2	R30-H6-D2		R15-H9-D8	R0-H6-D8
12	5	4	10	4	5	7	7	7	7		12	24
45	40	40	40	40	39	38	38	37	37		45	35
43	55	55	50	56	56	55	55	55	56		43	41
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Winter_East

R15-H6-D8	R0-H6-D6	R0-H9-D2	R15-H8-D2	R0-H8-D4	R15-H8-D8	R15-H7-D8	R15-H7-D2	R15-H9-D2	R45-H7-D2		R15-H6-D8	R15-H9-D8
50	57	42	37	56	53	51	40	39	44		50	56
36	31	31	31	29	29	29	29	29	28		36	20
14	12	26	32	15	18	20	31	32	28		14	24
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Winter_North

R30-H9-D2	R15-H9-D2	R30-H7-D2	R30-H8-D2	R15-H8-D2	R45-H9-D2	R45-H8-D2	R30-H9-D4	R45-H6-D2	R45-H7-D2		R30-H9-D2	R15-H8-D4
43	44	45	45	45	45	46	46	46	47		43	55
57	56	55	55	55	55	54	54	54	53		57	45
0	0	0	0	0	0	0	0	0	0		0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Winter_West

R30-H7-D4	R30-H6-D2	R15-H8-D2	R30-H9-D4	R45-H7-D2	R0-H9-D2	R30-H9-D2	R30-H7-D2	R0-H8-D2	R15-H9-D2		R30-H7-D4	R0-H7-D2
22	20	18	26	21	21	21	21	20	18		22	23
21	21	21	20	20	20	20	20	20	20		21	17
56	59	61	55	59	60	60	60	60	62		56	60
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.16 Data for seasonally optimized adjustable light shelf for Winter, Blacksburg, VA

Blacksburg_Seasonally Adjustable_Spring_South

R0-H6-D8	R15-H9-D8	R15-H7-D8	R0-H7-D8	R15-H9-D6	R15-H8-D6	R0-H7-D6	R15-H8-D8	R15-H7-D6	R15-H8-D4		R0-H6-D8	R0-H6-D8
14	6	2	17	6	2	13	4	2	2		14	14
75	68	68	64	64	64	63	63	62	62		75	75
11	26	31	19	31	35	24	33	36	36		11	11
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Spring_East

R15-H8-D8	R15-H9-D4	R15-H8-D4	R15-H9-D8	R15-H8-D6	R0-H7-D2	R15-H9-D6	R30-H7-D4	R30-H8-D4	R30-H6-D2		R15-H8-D8	R15-H9-D8
38	31	34	40	37	29	38	31	31	31		38	40
40	39	36	36	36	35	33	33	31	31		40	36
21	31	30	25	27	36	29	36	37	38		21	25
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Spring_North

R15-H7-D2	R15-H8-D2	R15-H9-D2	R30-H7-D2	R30-H6-D2	R30-H9-D2	R0-H8-D2	R30-H8-D2	R0-H9-D2	R15-H9-D4		R15-H7-D2	R15-H7-D2
31	32	32	34	35	35	36	36	36	36		31	31
69	68	68	66	65	65	64	64	64	64		69	69
0	0	0	0	0	0	0	0	0	0		0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Spring_West

R30-H7-D8	R30-H8-D6	R30-H7-D6	R30-H6-D8	R30-H9-D8	R30-H7-D4	R15-H9-D6	R30-H6-D4	R30-H9-D6	R15-H9-D8		R30-H7-D8	R0-H7-D2
34	31	31	31	31	30	32	30	30	36		34	25
23	22	21	21	20	19	18	18	18	17		23	17
43	47	48	48	50	51	50	52	52	47		43	58
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.17 Data for seasonally optimized adjustable light shelf for Spring, Blacksburg, VA

Blacksburg_Seasonally Adjustable_Summer_South

R0-H6-D6	R0-H6-D8	R15-H7-D8	R15-H6-D8	R0-H7-D6	R15-H8-D8	R0-H7-D8	R15-H7-D6	R15-H9-D8	R15-H8-D6		R0-H6-D6	R0-H6-D8
2	6	2	0	7	3	12	2	5	2		2	6
96	93	93	93	89	88	86	85	84	84		96	93
2	1	5	7	3	9	2	13	11	14		2	1
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Summer_East

R15-H9-D8	R15-H8-D6	R15-H8-D4	R0-H7-D8	R15-H8-D8	R0-H6-D8	R15-H9-D6	R15-H6-D2	R0-H8-D6	R0-H9-D4		R15-H9-D8	R15-H9-D8
22	18	15	44	20	40	22	14	40	31		22	22
51	48	48	47	47	45	45	44	43	42		51	51
26	34	37	9	33	15	32	42	17	26		26	26
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Summer_North

R15-H8-D2	R15-H8-D4	R15-H7-D4	R15-H9-D4	R15-H7-D2	R15-H9-D2	R15-H7-D6	R0-H7-D2	R15-H6-D2	R0-H9-D2		R15-H8-D2	R15-H7-D2
17	21	21	21	21	17	22	22	22	22		17	21
83	79	79	79	79	79	78	78	78	78		83	79
0	0	0	0	0	5	0	0	0	0		0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Summer_West

R15-H9-D8	R15-H9-D6	R15-H6-D4	R15-H6-D6	R15-H8-D4	R15-H7-D6	R15-H8-D6	R15-H7-D4	R0-H9-D4	R15-H6-D8		R15-H9-D8	R0-H7-D2
18	11	9	11	10	12	11	10	29	14		18	12
54	53	45	45	45	44	44	44	43	43		54	34
28	36	45	45	45	45	45	46	28	43		28	54
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.18 Data for seasonally optimized adjustable light shelf for Summer, Blacksburg

Blacksburg_Seasonally Adjustable_Fall_South

R0-H6-D8	R0-H7-D8	R0-H7-D6	R0-H8-D6	R15-H9-D6	R15-H9-D8	R0-H9-D4	R0-H6-D6	R15-H8-D8	R0-H8-D4		R0-H6-D8	R0-H6-D8
0	2	2	7	0	1	4	1	0	2		0	0
76	71	68	67	64	64	60	60	60	59		76	76
24	26	30	26	36	36	36	39	40	39		24	24
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Fall_East

R0-H7-D2	R30-H7-D4	R15-H9-D4	R15-H8-D4	R15-H9-D8	R15-H6-D2	R15-H9-D6	R30-H7-D6	R15-H8-D6	R30-H9-D8		R0-H7-D2	R15-H9-D8
21	29	26	26	31	21	30	31	27	31		21	31
39	31	31	31	31	31	30	29	29	28		39	31
40	40	42	43	38	48	40	40	44	40		40	38
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Fall_North

R15-H7-D2	R15-H8-D2	R15-H9-D2	R15-H9-D4	R0-H9-D2	R30-H8-D2	R30-H9-D2	R30-H6-D2	R0-H7-D2	R30-H7-D2		R15-H7-D2	R15-H7-D2
28	29	29	30	30	30	30	31	31	31		28	28
72	71	71	70	70	70	70	69	69	69		72	72
0	0	0	0	0	0	0	0	0	0		0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Blacksburg_Seasonally Adjustable_Fall_West

R15-H9-D6	R15-H8-D4	R15-H9-D8	R15-H7-D8	R30-H7-D8	R15-H9-D2	R15-H6-D6	R15-H8-D6	R30-H7-D6	R15-H8-D8		R15-H9-D6	R0-H7-D2
21	18	26	21	31	17	22	22	27	24		21	20
31	31	28	27	26	26	26	26	25	25		31	22
47	51	45	52	42	56	52	52	48	51		47	58
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.19 Data for seasonally optimized adjustable light shelf for Fall, Blacksburg, VA

Miami_Fixed Light Shelf_Best Annual_South

R0-H6-D8	R15-H9-D8	R0-H7-D8	R0-H7-D6	R15-H9-D6	R15-H8-D8	R15-H7-D8	R15-H6-D8	R0-H6-D6	R15-H8-D6		R0-H6-D8	No Light Shelf
5	3	12	7	5	2	2	0	3	2		5	2
77	70	68	67	67	67	65	64	64	63		77	53
18	26	20	26	28	31	33	36	33	36		18	45
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Miami_Fixed Light Shelf_Best Annual_East

R45-H6-D6	R45-H7-D8	R45-H7-D4	R30-H9-D8	R30-H8-D8	R15-H9-D4	R15-H9-D8	R45-H9-D2	R30-H6-D4	R30-H7-D8		R45-H6-D6	No Light Shelf
17	22	38	20	22	14	11	40	16	40		17	12
50	50	46	45	45	44	44	42	42	40		50	36
32	28	16	35	33	42	45	17	42	19		32	53
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Miami_Fixed Light Shelf_Best Annual_North

R0-H8-D8	R30-H8-D8	R15-H8-D8	R0-H9-D4	R15-H7-D2	R30-H7-D8	R0-H9-D8	R45-H7-D2	R0-H7-D6	R15-H9-D4		R0-H8-D8	No Light Shelf
24	26	28	28	29	21	30	31	31	24		24	24
76	74	72	72	71	71	70	69	69	69		76	55
0	1	0	0	0	7	0	0	0	7		0	21
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Miami_Fixed Light Shelf_Best Annual_West

R15-H6-D8	R15-H8-D2	R30-H9-D6	R0-H8-D2	R15-H9-D8	R0-H6-D8	R15-H6-D6	R45-H9-D6	R15-H7-D8	R45-H7-D6		R15-H6-D8	No Light Shelf
21	8	7	5	5	4	7	6	5	4		21	5
44	44	43	42	41	41	40	40	40	40		44	31
36	48	50	53	54	55	52	54	55	55		36	64
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	No L.Shelf

Fig. A.20 Data for annually optimized fixed light shelf for Miami, FL

Miami_Seasonally Adjustable_Winter_South

R0-H7-D8	R0-H6-D8	R0-H8-D8	R0-H7-D6	R15-H9-D8	R15-H9-D6	R0-H9-D4	R0-H8-D6	R15-H8-D8	R0-H8-D4		R0-H7-D8	R0-H6-D8
2	0	8	1	1	0	2	2	0	2		2	0
71	70	69	68	68	68	67	66	66	65		71	70
27	30	23	31	31	32	31	31	34	33		27	30
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Winter_East

R0-H6-D6	R15-H6-D8	R15-H7-D8	R15-H8-D8	R15-H8-D4	R15-H9-D6	R15-H9-D8	R15-H7-D6	R15-H8-D6	R30-H7-D4		R0-H6-D6	R15-H8-D8
40	33	34	34	29	34	34	33	31	30		40	34
38	38	37	36	36	36	36	35	35	35		38	36
22	29	29	30	35	31	31	32	35	36		22	30
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Winter_North

R15-H7-D2	R15-H9-D2	R30-H7-D2	R15-H8-D2	R30-H6-D2	R30-H9-D2	R0-H8-D2	R30-H8-D2	R30-H8-D4	R15-H9-D4		R15-H7-D2	R15-H8-D4
31	31	32	32	34	34	35	36	36	36		31	40
69	69	68	68	66	66	65	64	64	64		69	60
0	0	0	0	0	0	0	0	0	0		0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Winter_West

R15-H8-D8	R15-H7-D6	R15-H7-D8	R15-H6-D4	R0-H8-D4	R15-H6-D6	R15-H6-D8	R15-H9-D6	R0-H6-D2	R15-H7-D4		R15-H8-D8	R0-H6-D8
8	6	6	5	12	6	6	9	7	6		8	21
36	34	34	34	33	33	33	32	32	32		36	23
55	60	60	61	55	61	61	59	61	62		55	55
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.21 Data for seasonally optimized adjustable light shelf for Winter, Miami, FL

Miami_Seasonally Adjustable_Spring_South

R0-H6-D8	R0-H7-D8	R0-H7-D6	R15-H8-D8	R0-H6-D6	R15-H8-D6	R15-H7-D8	R15-H9-D8	R15-H9-D6	R0-H8-D4		R0-H6-D8	R0-H6-D8
2	7	4	1	2	1	1	2	2	7		2	2
95	88	86	81	79	79	79	78	76	74		95	95
2	5	10	18	18	21	21	21	21	20		2	2
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Spring_East

R15-H9-D8	R15-H9-D6	R0-H6-D8	R15-H8-D8	R15-H8-D4	R0-H9-D4	R0-H9-D8	R0-H6-D2	R0-H6-D4	R15-H8-D6		R15-H9-D8	R15-H8-D8
20	20	36	17	12	28	38	14	18	17		20	17
50	44	43	43	42	41	40	40	40	39		50	43
30	36	21	40	45	31	21	45	42	44		30	40
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Spring_North

R15-H8-D2	R15-H8-D4	R15-H7-D2	R15-H9-D2	R15-H7-D4	R15-H6-D2	R0-H7-D2	R0-H9-D2	R15-H9-D4	R15-H6-D4		R15-H8-D2	R30-H8-D4
21	23	24	24	24	26	26	26	26	26		21	30
79	77	76	76	76	74	74	74	74	74		79	70
0	0	0	0	0	0	0	0	0	0		0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Spring_West

R0-H6-D8	R15-H6-D6	R15-H6-D8	R15-H7-D4	R15-H7-D6	R15-H7-D8	R15-H6-D4	R15-H8-D4	R0-H6-D4	R0-H6-D2		R0-H6-D8	R0-H6-D8
7	0	1	1	2	2	1	2	4	2		7	7
42	42	41	40	40	40	40	39	38	38		42	42
50	58	58	59	59	59	60	60	58	60		50	50
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.22 Data for seasonally optimized adjustable light shelf for Spring, Miami, FL

Miami_Seasonally Adjustable_Summer_South

R15-H6-D8	R15-H7-D8	R15-H6-D6	R0-H6-D6	R15-H7-D6	R0-H7-D4	R15-H8-D8	R0-H6-D4	R15-H8-D4	R0-H7-D6		R15-H6-D8	R0-H6-D8
3	7	5	9	7	9	7	7	6	17		3	18
97	93	92	91	91	90	90	90	84	83		97	82
0	0	3	0	2	1	2	3	10	0		0	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Summer_East

R15-H8-D8	R15-H9-D8	R15-H9-D6	R15-H9-D4	R0-H6-D8	R15-H7-D2	R0-H8-D4	R15-H8-D6	R15-H8-D4	R0-H7-D8		R15-H8-D8	R15-H8-D8
11	12	15	8	31	6	22	8	7	36		11	11
62	61	57	54	51	50	49	49	49	48		62	62
27	27	28	38	17	45	29	43	44	16		27	27
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Summer_North

R15-H8-D4	R15-H7-D4	R15-H6-D4	R15-H7-D6	R15-H6-D6	R15-H7-D8	R15-H8-D8	R15-H8-D6	R15-H6-D8	R15-H9-D4		R15-H8-D4	R15-H8-D4
8	10	12	12	13	14	14	15	16	8		8	8
91	90	88	88	87	86	86	85	84	84		91	91
1	0	0	0	0	0	0	0	0	7		1	1
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Summer_West

R15-H9-D8	R15-H9-D6	R15-H8-D8	R15-H6-D8	R0-H6-D8	R15-H7-D8	R15-H8-D4	R15-H6-D6	R15-H7-D6	R15-H6-D4		R15-H9-D8	R0-H6-D8
7	2	4	1	17	2	2	2	2	1		7	17
65	61	56	56	55	53	53	53	53	53		65	55
28	37	40	43	28	45	45	45	45	46		28	28
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Data for seasonally optimized adjustable light shelf for Summer, Miami, FL

Miami_Seasonally Adjustable_Fall_South

R0-H6-D8	R0-H6-D6	R0-H7-D6	R0-H7-D8	R15-H8-D8	R15-H7-D8	R15-H8-D6	R15-H9-D6	R15-H9-D8	R15-H6-D8		R0-H6-D8	R0-H6-D8
3	2	5	7	1	1	1	2	2	0		3	3
94	87	86	85	81	80	79	79	79	78		94	94
2	12	9	7	18	19	20	20	20	22		2	2
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Fall_East

R15-H9-D8	R15-H8-D8	R0-H6-D8	R0-H8-D4	R15-H8-D4	R15-H8-D6	R15-H6-D2	R15-H7-D4	R0-H6-D2	R15-H6-D4		R15-H9-D8	R15-H8-D8
15	12	34	26	9	10	9	12	11	11		15	12
50	49	44	43	42	41	41	40	40	40		50	49
35	39	22	31	49	49	50	47	49	49		35	39
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Fall_North

R15-H8-D2	R15-H7-D2	R15-H8-D4	R15-H9-D4	R0-H7-D2	R0-H8-D2	R15-H7-D4	R15-H6-D2	R30-H7-D4	R15-H8-D6		R15-H8-D2	R15-H8-D4
18	23	23	24	25	26	26	24	26	26		18	23
81	77	77	76	75	74	74	74	74	74		81	77
1	0	0	0	0	0	0	2	0	0		1	0
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Miami_Seasonally Adjustable_Fall_West

R0-H6-D8	R15-H9-D8	R15-H8-D8	R0-H7-D8	R15-H6-D6	R15-H9-D6	R0-H8-D4	R15-H7-D4	R15-H8-D4	R15-H7-D8		R0-H6-D8	R0-H6-D8
17	7	5	23	1	1	10	1	1	3		17	17
57	55	54	51	48	48	47	47	47	46		57	57
26	38	41	26	51	51	43	52	52	50		26	26
100	100	100	100	100	100	100	100	100	100		100	100
Best	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		Best Adj.	Best Fixed

Fig. A.23 Data for seasonally optimized adjustable light shelf for Fall, Miami, FL

Appendix B: Statistical Analysis Resources

The analysis was done with the software 'R'. A copy of the script used is shown in Fig. B.1.

```
# These first few lines read in the data and format it in a way R understands. If you want to run this code, make sure the file is in the
working directory or else you'll need to change the address of the function on line 3.

light = read.csv("fourseasons.csv")
light = transform(light, Rotation = as.factor(Rotation), Height = as.factor(Height), Depth = as.factor(Depth), Season = as.factor(Season))

agg.light = with(light, aggregate(DL_Auto, list(Rotation, Height, Depth, Season), mean))
agg.light = transform(agg.light, Rotation = Group.1, Height = Group.2, Depth = Group.3, Season = Group.4, DL_Auto = x)

# These lines create the barplots

with(agg.light, plot(Rotation, DL_Auto, main = "Rotation"))
with(agg.light, plot(Height, DL_Auto, main = "Height"))
with(agg.light, plot(Depth, DL_Auto, main = "Depth"))
with(agg.light, plot(Season, DL_Auto, main = "Season"))

# Here are a bunch of different models I ran as I tried to find a good one. Eventually I settled on the last one in the list.

height.lm = with(agg.light, lm(DL_Auto ~ Height))
rotation.lm = with(agg.light, lm(DL_Auto ~ Rotation))
depth.lm = with(agg.light, lm(DL_Auto ~ Depth))

all.lm = with(agg.light, lm(DL_Auto ~ Height + Rotation + Depth))
noheight.lm = with(agg.light, lm(DL_Auto ~ Rotation + Depth + Season))

c0.light = with(light, aggregate(DL_Auto, list(R_actual, H_actual, D_actual, Sea_actual), mean))
c0.light = transform(c0.light, Rotation = Group.1, Height = Group.2, Depth = Group.3, Season = Group.4, DL_Auto = x)
c0.light = c0.light[,6:10]

c0.light = data.frame(c0.light, Rot2 = c0.light$Rotation^2)

c0.linear = with(c0.light, lm(DL_Auto ~ Depth + Rotation))

# This is the final model. I chose it because it fits well, though not the best. However, it is the simplest model which describes all the
interesting features of the data. In particular, it captures the linear nature of depth, the quadratic nature of rotation, and the absence
of significant interaction between the two. Height is not included since it was found to be insignificant.

c0.quad = with(c0.light, lm(DL_Auto ~ Depth + Rotation + Rot2 + Season))

# These last lines produce the residual diagnostic plots

par(mfrow = c(2, 2))
qqnorm(c0.quad$res, main = 'QQ-Normal Plot for Residuals')
qqline(c0.quad$res)
plot(c0.light$DL_Auto, c0.quad$res, main = "Residuals vs Fitted", xlab = "Fitted", ylab = "Residuals")
hist(c0.quad$res, main = "Residual Histogram", xlab = "Residuals")
plot(c0.quad$res, main = "Residual vs Order", xlab = "Order", ylab = "Residuals")
```

Fig. B.1 Script used in the statistical analysis of light shelf performance.

Results of the multiple regression analysis done with the software R is shown in Fig. B.2. Regression diagnostics are shown in Fig. B.3.

```
Call:
lm(formula = DL_Auto ~ Depth + Rotation + Rot2 + Season)

Residuals:
    Min      1Q  Median      3Q     Max
-11.6112 -1.6154 -0.1268  1.9859  7.4140

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  8.502e+01  6.149e-01 138.279  <2e-16 ***
Depth       -2.032e+00  8.005e-02 -25.389  <2e-16 ***
Rotation     6.404e-01  3.736e-02  17.142  <2e-16 ***
Rot2        -1.276e-02  7.955e-04 -16.037  <2e-16 ***
SeasonSpr   -5.742e+00  5.063e-01 -11.342  <2e-16 ***
SeasonSum    8.488e-01  5.063e-01   1.677  0.0949 .
SeasonWin   -1.403e+01  5.063e-01 -27.720  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 2.864 on 249 degrees of freedom
Multiple R-squared:  0.8913,	Adjusted R-squared:  0.8887
F-statistic: 340.2 on 6 and 249 DF,  p-value: < 2.2e-16
```

Fig. B.2 Results from the multiple regression analysis with 'R'.

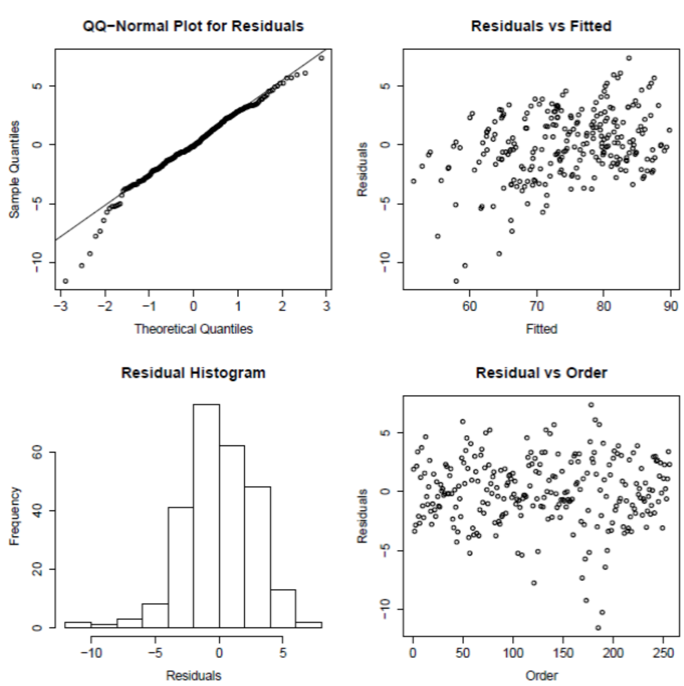


Fig. B.3 Regression Diagnostics.

Appendix C: Log of all experiments done for this research

	A	B	C	D	E	F	G	H	I	J	K
1	Date	9/27/2012			Date	9/27/2012			Date	9/27/2012	
2	Time	08:49.7			Time	08:49.1			Time	08:50.0	
3	X_Dimens	Time			X_Dimens	Time			X_Dimens	Time	
4	X0	0.00E+00			X0	0.00E+00			X0	0.00E+00	
5	Delta_X	1			Delta_X	1			Delta_X	1	
6	***End_of_Header***				***End_of_Header***				***End_of_Header***		
7	X_Value				X_Value		Comment		X_Value		Comment
8											
9	Sensor-1 (new / below light)				Sensor-2 (old / furthest from light)				Sensor-3 (old / (periphery of light)		
10	Time (s)	Volts	Light (lux)		Time (s)	Volts	Light (lux)		Time (s)	Volts	Light (lux)
11	0	0.29459	7365		0	0.094373	2359		0	0.136649	3416
12	1	0.296628	7416		1	0.094373	2359		1	0.138687	3467
13	2	0.296628	7416		2	0.094373	2359		2	0.138687	3467
14	3	0.314971	7874		3	0.100487	2512		3	0.146838	3671
15	4	0.312933	7823		4	0.100487	2512		4	0.146838	3671
16	5	0.29459	7365		5	0.094373	2359		5	0.138687	3467
17	6	0.29459	7365		6	0.094373	2359		6	0.138687	3467
18	7	0.292552	7314		7	0.094373	2359		7	0.136649	3416
19	8	0.317009	7925		8	0.100487	2512		8	0.148876	3722
20	9	0.304781	7620		9	0.098449	2461		9	0.142762	3569
21	10	0.304781	7620		10	0.098449	2461		10	0.142762	3569
22	11	0.292552	7314		11	0.094373	2359		11	0.136649	3416
23	12	0.300704	7518		12	0.096411	2410		12	0.142762	3569
24	13	0.296628	7416		13	0.096411	2410		13	0.138687	3467
25	14	0.298666	7467		14	0.096411	2410		14	0.138687	3467
26	15	0.29459	7365		15	0.094373	2359		15	0.138687	3467

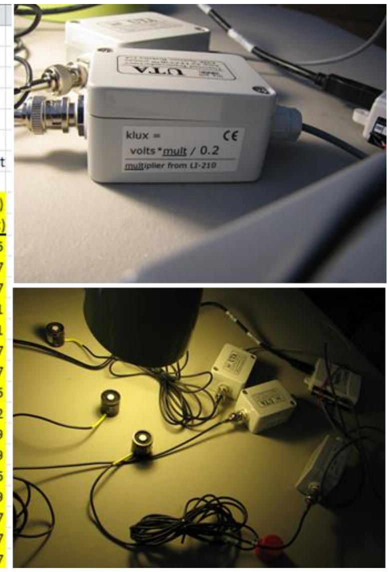


Fig. C.1 First data logging: Sep 27, 2012 (3 Li-Cor 210, UTA's and NI 6008 data logger

#	Date	#	Date	#	Date	#	Date	#	Date
1	27-Sep-12	11	16-Oct-12	21	5-Apr-13	31	23-Apr-13	41	29-May-13
2	2-Oct-12	12	18-Oct-12	22	6-Apr-13	32	25-Apr-13	42	30-May-13
3	4-Oct-12	13	23-Oct-12	23	7-Apr-13	33	26-Apr-13	43	1-Jun-13
4	6-Oct-12	14	20-Mar-13	24	9-Apr-13	34	7-May-13	44	3-Jun-13
5	7-Oct-12	15	25-Mar-13	25	11-Apr-13	35	7-May-13	45	4-Jun-13
6	9-Oct-12	16	26-Mar-13	26	12-Apr-13	36	8-May-13	46	7-Jun-13
7	11-Oct-12	17	29-Mar-13	27	14-Apr-13	37	9-May-13	47	8-Jun-13
8	12-Oct-12	18	30-Mar-13	28	15-Apr-13	38	13-May-13	48	11-Jun-13
9	13-Oct-12	19	3-Apr-13	29	16-Apr-13	39	15-May-13	49	13-Jun-13
10	15-Oct-12	20	4-Apr-13	30	21-Apr-13	40	28-May-13	50	22-Jun-13

Fig. C.2 Log of Experiments done using LiCor Li-210 photo sensors till June 2013

Appendix D: Ecotect and Radiance

At the initial phase of this research Ecotect was explored as a possible simulation program for this study. Ecotect has the capability of exporting its geometries to Radiance and import back the results for visualization and post processing. However, it proved difficult to program simulation loops in Ecotect that could run continuously without supervision and export results back into Excel for post-processing.

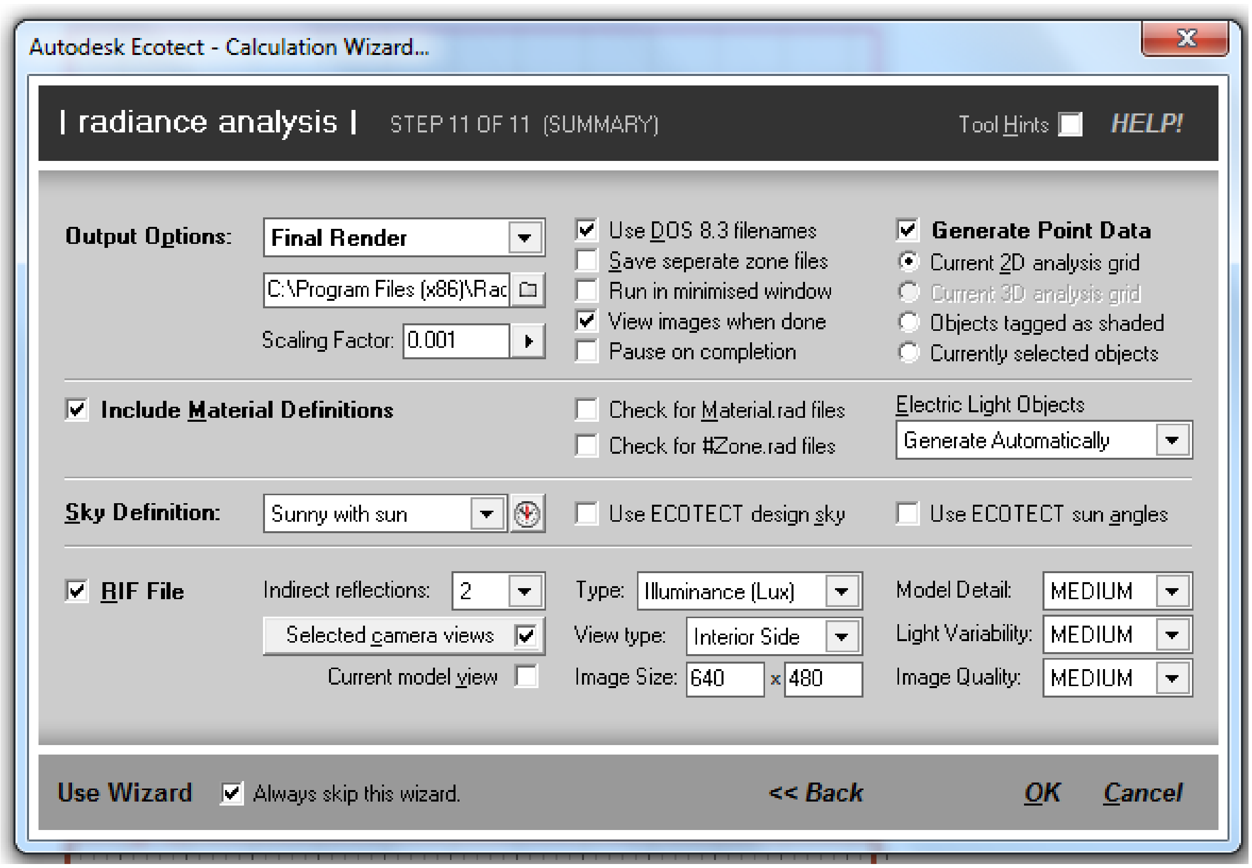


Fig. D.1 Ecotect as a front end to Radiance simulation

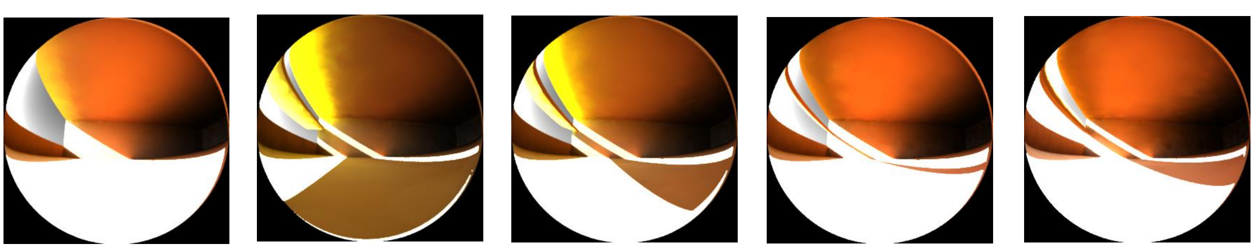


Fig. D.2 Radiance results visualized in Ecotect

Appendix E: Design, Construction and Use of a Tilt Table

A tilt table was constructed in the beginning of the experimental studies. It was dimensioned to hold a model that was a replica of the model used by Abdul Mohsen for his PhD at TAMU (Abdulmohsen, 1995). The idea was to try to replicate the results Abdul Mohsen has found by testing this model in direct sunlight. The tilt table allowed the model to be rotated in two axes. When used with a sun-dial the model could thus be rotated to mimic sunlight falling on it for a specific date and time of the year.

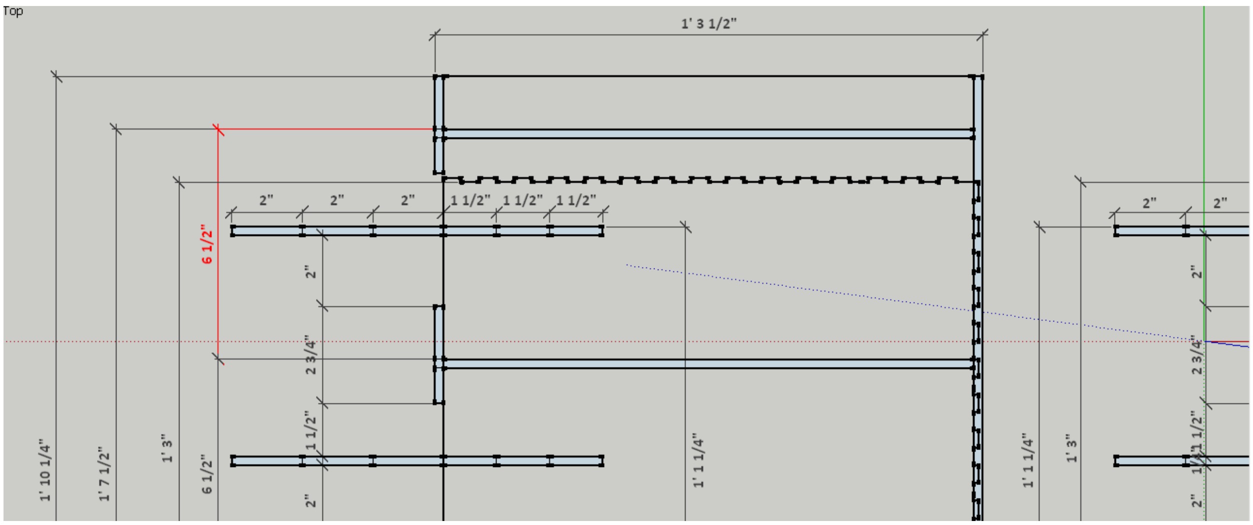


Fig. E.1 A replica of the model used by Abdul Mohsen for his PhD research at TAMU

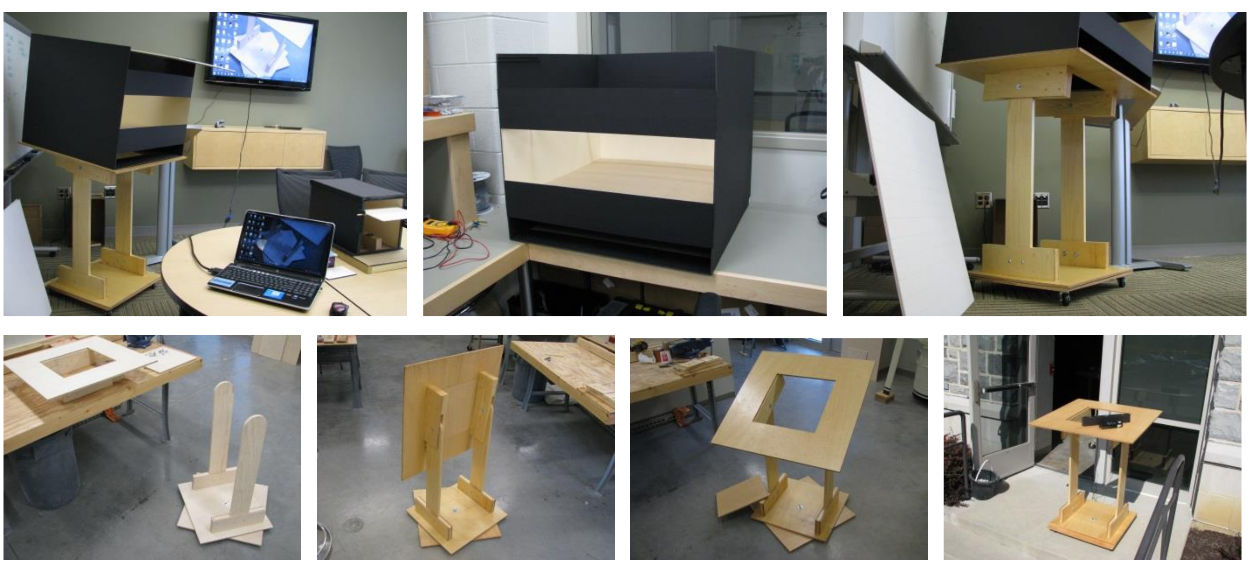


Fig. E.2 Tilt table construction and use with daylighting model

Appendix F: Mirror-Box artificial sky proposal for Virginia Tech

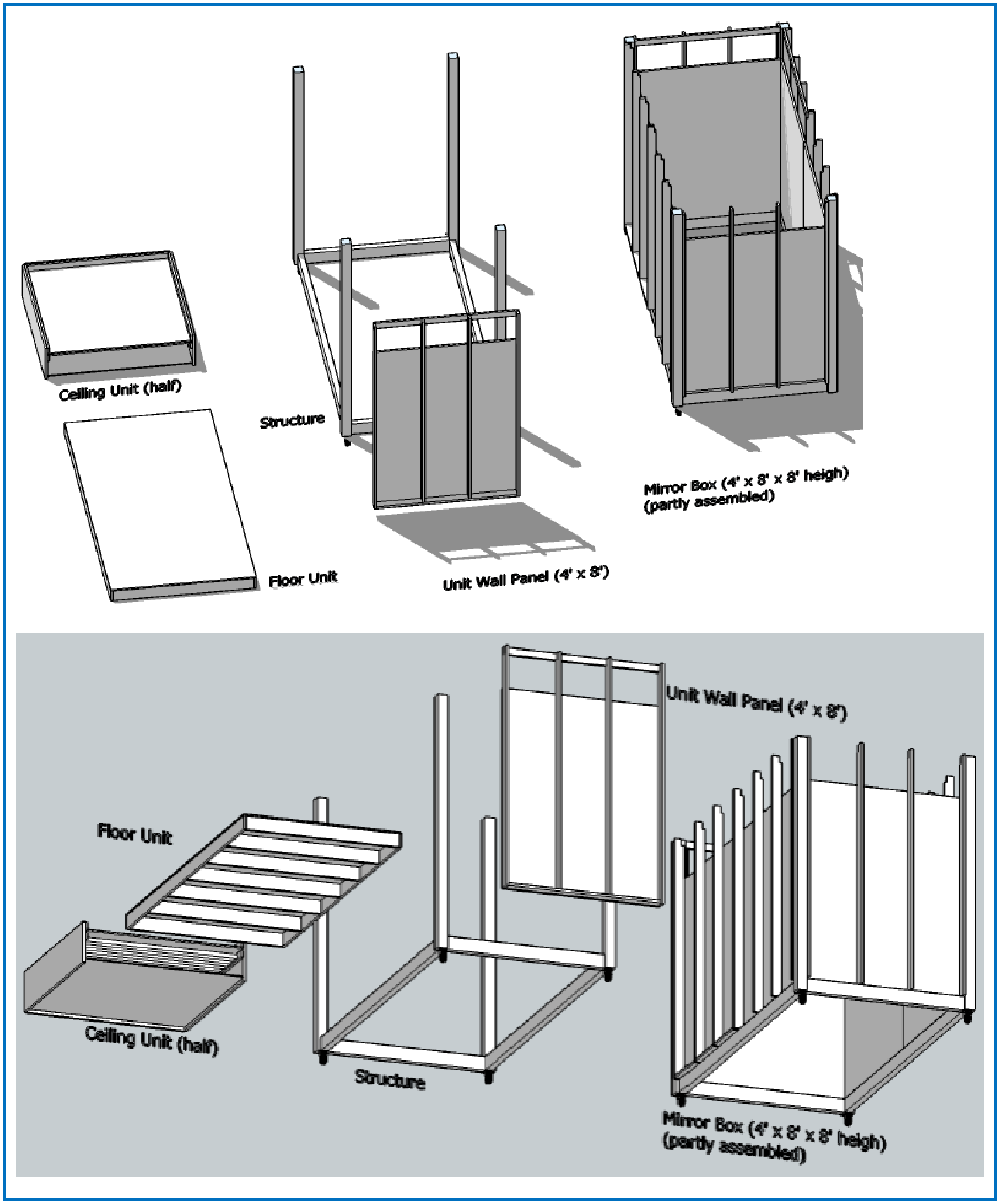


Fig. F.1 Mirror Box Design looking from above (top) and from below (bottom)