ABSTRACT

GHOBAD, LADAN. Analysis of Daylighting Performance and Energy Savings in Roof Daylighting Systems. (Under the direction of Dr. Wayne Place).

An investigation has been made of potential lighting electricity reductions and associated thermal impacts of replacing electric light with daylight admitted through rooftop glazing. Horizontal apertures on flat roof (skylights) and vertical apertures facing in two opposite directions (roof monitors) are examined in a prototype office building. A computer simulation tool that integrates lighting simulation (RADIANCE) and energy simulation (EnergyPlus), DIVA-for-Rhino has been used. Lighting simulation determines the fraction of the solar radiation entering the aperture that reaches the work plane as useful illumination; whole-building energy simulation predicts reductions in lighting electricity and the impact on energy consumption for heating and cooling the building. Building operation costs are calculated as a function of aperture to floor area so that the optimum roof daylighting design could be identified. The results indicate that rooftop glazing contribute to savings in building operation if a modest amount of glazing is used in the roof. In some climates either heating or cooling energy is more sensitive to increasing the area of glazing, but the potential cost benefits of daylighting are larger when an optimum aperture area is used. The design implications of the results are discussed and important parameters that influence the rooflit building operation costs will be outlined.
Analysis of Daylighting Performance and Energy Savings in Roof Daylighting Systems

by
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DEDICATION

I dedicate this dissertation to my beloved family. Particularly to my understanding and patient husband, Amir Taefi, whose love, encouragement and companionship made this work happen. A special feeling of gratitude to my loving parents, Sezar Ghobad and Parvin Adibi, who embraced me with love and supported me throughout my life.
BIOGRAPHY

Ladan Ghobad joined the Daylighting and Building Energy Research Program at the North Carolina State University (NCSU) at 2009 after nine years of education and professional work in the field of Architecture. She received her Bachelor’s and Master’s Degree in Architecture from the Islamic Azad University of Tehran and the Shahid Beheshti University, two prestigious universities in Iran, Tehran. As a Ph.D. student at NCSU, Ladan has developed studies about Daylighting Systems Integration in Buildings as a research assistant as well as working as a teaching assistant. Ladan Ghobad has worked at the Building Technology Lab MIT as a research intern and collaborated as a teaching assistant with special focus on emerging methods of building science education in architecture departments.
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SkyCalc, THERM/WINDOW

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CHAPTER 1: INTRODUCTION

1.1. PROBLEM AREA

Daylighting is a crucial element in buildings design due to its psychological and physiological effects, and impact on energy consumption in buildings.

First, human beings need regular exposure to daylight to maintain health. By nature, people prefer rooms with natural light because they are dynamic, creating variability in both space and time. Natural light is also full-spectrum light that provides excellent color rendering. In addition to the sense of well being associated with natural light, there appears to be a correlation between daylight levels in a space and the productivity of the occupants of the space (Heschong Mahone Group, 2003).

Moreover, daylighting can reduce energy use in buildings significantly. Buildings in America consume about 39% of the primary energy use and 70% of the total electricity use (Department of Energy, 2010). Among all building types, commercial buildings are the major consumers of electricity. In these buildings, approximately a quarter of the total energy is consumed for providing electric lighting (CBECS 2003). Approximately another three percent is consumed for cooling. Furthermore, buildings account for a substantial fraction of the peak electricity demand on U.S. utilities (ASHRAE). All of these issues can be beneficially affected by using daylight as a substitute for electric light to illuminate buildings. Daylighting buildings is attractive for several reasons:

- During most working hours, the solar illumination on a building is several times greater than the required amount to illuminate the interior, indicating that it would be possible to design solar apertures that provide enough illumination to offset most of the lighting electricity consumption.

- The luminous efficacy of sunlight is generally superior to that of commercially available electric lamps with acceptable color rendering, which means that daylight has the potential for reducing building cooling loads by replacing electric light of higher heat content.

- Daylight is plentiful during the hot, clear, summer periods when many utilities experience their peak demand, suggesting that there is potential for reducing demand for both lighting and cooling electricity, with consequent demand charge savings for the building owners and reduced capacity requirements for the utility.
Roof daylighting systems in particular are an interesting daylighting technique, because:

- The potential impact is very large; on the order of 50% of the commercial building floor area in the United States is in single-story buildings or the top floor of multistory buildings (DOE/EIA 1983).

- The solar exposure is generally good for sprawling single-story buildings or for the top floor of multistory buildings.

- Roof apertures allow a choice of glazing orientation and tilt, which is crucial in using passive techniques to regulate the flow of sunlight into the building; i.e., in compensating for seasonal and diurnal variations in the direction and intensity of solar radiation.

- Roof apertures have both new and retrofit potential.

- The illuminance can be made highly uniform by using closely spaced apertures.

- The quality of lighting can be very high, since: 1) the source of light can be located up out of the primary field of view, thereby avoiding most of the visual discomfort associated with viewing the light source, and 2) diffusing glazing (or other optical treatments) can be used to disperse the light around the space, thereby avoiding the extreme contrast associated with allowing beam sunlight to impinge on the work surface.

However, toplighting has not been extensively used in commercial buildings in the United States because of concerns regarding its daylight and energy performance, liability for water leakage and concerns regarding the initial cost of the system (Lawrance & Roth, 2008). In addition, the energy payback potential is quite high.

One reason for having a limited market is that roof daylighting systems are improperly selected and designed, therefore, the benefits of electric lighting energy reduction are negated due to higher space conditioning requirements and lower visual quality of environment (Yoon, 2008).

Also, prevailing perceptions regarding the performance of roof daylighting systems are strongly influenced by failures of skylights, which are the most widely experienced roof daylighting systems.

In addition, most topliting configurations other than skylights require special structural design, which becomes a major hindrance for market penetration in the cost-conscious building industry, particularly in mid-scale and small-scale construction projects.
1.2. RESEARCH GOALS

This study assesses the potential for reducing energy consumption in commercial buildings using simple roof apertures (e.g. skylights and roof monitors) constructed with current technology. The current research provides grounds for a guideline for designers to choose the appropriate configuration of roof apertures. Research goals could be categorized into the following items:

- Investigate the problems that have lowered the quality of lighting and energy performance of current rooflighting systems and, as a consequence, reduced their market penetration.

- Define a range of common or promising rooflighting configurations, including construction details, structural sizing, and selective construction cost assessments, for a range of climates.

- Simulate and evaluate the daylighting effectiveness for special configurations of rooflighting systems.

- Simulate and evaluate the thermal performance of the special configurations of rooflighting systems.

- Estimate savings in energy consumption and building operation costs through application of the suggested roof daylighting systems.

- Design optimization of roof daylighting systems based on energy consumption and building operation costs.
CHAPTER 2: REVIEW OF THE LITERATURE

2.1. ROOF DAYLIGHTING SYSTEMS: STATE OF THE ART

2.1.1. Definition of Roof-daylighting Systems

Roof daylighting, also referred to as toplighting, rooflighting and zenithal lighting, by definition is a strategy that permits daylight to enter a space from above, through a glazed opening in the roof that protects the interior from wind and weather (Phillips, 2004). Toplighting is differentiated from clerestories in the literature (Ander, 2003); clerestory is defined as vertical or near-vertical windows whose sill height is above eye level but below ceiling height, whereas, toplighting is defined as apertures located above the ceiling line. In other words, toplighting usually constitutes part of the roof of a building in contrast to clerestory windows, which are located in the upper part of the wall.

A rooflighting system typology using nomenclature of the Chartered Institution of Building Services Engineers (CIBSE) is shown in figure 1. It includes: flat, shed, domes, north-light, sawtooth, and monitor.

![Figure 1. CIBSE Rooflights Typology](image)

Skylights are defined simply as horizontal glazed roof apertures that are parallel or nearly parallel to the roof; roof monitors are raised building elements of a roof with vertical or sloped apertures on one or more sides (Ander, 2003).
The resulting illuminance on horizontal surfaces from the toplighting systems is greater than sidelights with the same opening surface area because of four reasons (Tregenza 2011, Place et al. 1886):

- Light is incident on the horizontal aperture at a favorable angle for admission through the aperture.
- The light admitted through the apertures is at a very favorable angle for illuminating the work plane below.
- The openings receive light from a larger area of sky.
- Overcast sky tends to be brightest at the zenith.

In addition, toplighting strategies can resolve many of the problems with light distribution resulted from sidelighting and depth of plan is no longer a limitation (Baker, 2002). It is obvious, however, that only single-story buildings or the top floors of multi-story buildings can be rooflit. Some other typical problems for rooms with rooflighting include (Tregenza, 2011):

- Poor illumination of vertical surfaces and therefore a general dark look of the room unless openings are planned to cast light on walls.
- High brightness contrast on the ceiling between the visible sky and the surrounding ceiling area since it is only illuminated by light reflections.
- Unwanted specular reflections of the sky in horizontal work surfaces in some occasions

**Definition of terms:** this section includes some terms used in the literature related to roof daylighting systems and evaluation of their performance.

**Skylight to Floor Area Ratio (SFR)**

SFR is defined as the gross area of opening divided by the floor area (Heshong Mahone Group 2003, 2008). Since SFR is associated only with skylights, in the current research, AFR (Aperture to Floor Area Ratio) replaces SFR to include a wide range of roof daylighting systems such as roof monitors as well as skylights.
**Effective Aperture (EA)**

EA is defined as the net transmittance of the roof. Effective aperture is product of the skylight-to-floor ration (SFR), the visible transmittance (Tv) and the well factor. Values of EA range from 0 to 1.0, with most practical skylights at less than 0.1 (Heshong Mahone Group 2003).

**Effective Visual Transmittance (EVT)**

EVT is defined as the ratio of the light transmitted through a daylighting system (skylight+ light well diffusers and etc.) to the light incident on the horizontal projection of the roof’s opening (McHugh et. Al 2004).

**Well cavity ratio (WCR)**

The well cavity ratio is determined by the geometry of the skylight well and shall be determined using either equation 1 or equation 2.

Equation 1: well cavity ratio for rectangular wells:

\[ WCR = \frac{5 \times \text{well height} \times (\text{well length} + \text{well width})}{\text{well length} \times \text{well width}} \]  

(Equ1)

Equation 2 well cavity ratio for non-rectangular-shaped wells:

\[ WCR = \frac{2.5 \times \text{well height} \times \text{well perimeter}}{\text{well area}} \]  

(Equ2)

Where the length, width, perimeter, and area are measured at the bottom of the well.

**Well Efficiency**

Well efficiency is the ratio of the amount of visible light leaving a skylight well to the amount of visible light entering the skylight well (Heshong Mahone Group 2003). Well efficiency is determined from figure 2 based on the weighted average reflectance of the walls of light-well and the well cavity ratio (WCR), or other test method approved by the Commission (Codes and Standards Enhancement Initiative CASE, 2006).
2.1.2. Case Studies of Roof-daylighting Systems

This section investigates case studies of roof daylighting systems in Europe and United States. Case studies cover various building types including museums, libraries, schools, sport facilities, terminals, airports, and office buildings. The illustrated case studies are a few examples of existing roof daylighting systems; providing a complete list of buildings was beyond the scope of this research. For each case, information about the location, built year, architect, daylighting system is provided.
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Architect:</strong> Thomas Phifer and Partners (local architect: Pearce Brinkley Cease + Lee)</td>
<td><strong>Architect:</strong> Renzo Piano</td>
<td><strong>Architect:</strong> Renzo Piano</td>
</tr>
<tr>
<td><strong>Daylighting system:</strong> 362 Horizontal apertures, called &quot;elliptical oculi&quot;, which are located in long, parallel, coffered vaults</td>
<td><strong>Daylighting system:</strong> glazed sawtooth roof facing north and a horizontal layer of translucent glass underneath Daylighting Control System: large overhangs on the tilted edges of the sawtooth roof Climate: Moderate marine climate</td>
<td><strong>Daylighting system:</strong> numerous light scoops creating clear glass shadowed by lipstick shades facing north. Daylighting Control System: Fiberglass-reinforced molded gypsum shades Climate: Warm and humid</td>
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<tr>
<td><strong>Daylighting Control System:</strong> Curved panels with blades on top of the roof Climate: Mixed hot and cold</td>
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<tr>
<td><strong>Architect:</strong> Renzo Piano</td>
<td><strong>Architect:</strong> Renzo Piano</td>
<td><strong>Architect:</strong> Renzo Piano</td>
</tr>
<tr>
<td><strong>Daylighting system:</strong> Multilayer roof composed of exterior tilted glazing connected two by two and giant louveres. Daylighting Control System: Exterior curved louvers; called “leaves”, control daylight from the roof. In the galleries, the curve of the &quot;leaf&quot; blocks direct sunlight and scatters the light reflected off the neighboring leaf. Climate: Hot and Humid climate</td>
<td><strong>Daylighting system:</strong> Sawtooth louveres facing north built on top of horizontal structural layer of glass Daylighting Control System: exterior tilted louvers made of translucent laminated glazing material and interior horizontal louveres made of metal mesh frames Climate: Temperate</td>
<td><strong>Daylighting system:</strong> double-layer roof composed of slightly curved glass vaults with aluminum sunshade panels on top. Daylighting Control System: cast aluminum sun-shading panels with round holes facing towards north Climate: Warm and humid</td>
</tr>
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*Table 1 Case studies of roof daylighting systems*
<table>
<thead>
<tr>
<th>Location</th>
<th>Architect</th>
<th>Design Details</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBU Conference and Exhibition pavilion, Osnabruch, Germany (2002)</td>
<td>Herzog+ partners</td>
<td>Daylighting system: modular roof made of an exterior layer of transparent ETFE film. Beneath this weatherproof membrane, numerous multi-layer roof constructions are conceivable, which can be matched to the respective use of the interior. In the exhibition area, the roof bays have translucent double-glazing but no thermal insulation. Daylighting Control System: louver system on top of the glazing material underneath the exterior ETFE layer. Climate: temperate</td>
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<tr>
<td>Wallraf-Richartz-Museum, Cologne, Germany (1986), Architect: Peter Bussman and Godfrid Haberer</td>
<td></td>
<td>Daylighting system: Curved rooflights with tilted monitors facing north Daylighting Control System: External vertical metal sheets and internal motorized roller blinds Climate: temperate-oceanic climate with relatively mild winters and warm summers Notes: Theoretically, museum offers great opportunities for energy saving. However, the blinds tend to be closed most of the time, which requires artificial lighting in the galleries.</td>
<td></td>
</tr>
<tr>
<td>Kimbell Art Museum, Fort Worth, Texas (1972)</td>
<td>Architect: Louis Kahn</td>
<td>Daylighting system: linear horizontal aperture in the center of vaults Daylighting Control System: two curved aluminum foils, which reflect light to each half part of the vault Climate: Hot and dry</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Architect</td>
<td>Daylighting System</td>
<td>Daylighting Control System</td>
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<tr>
<td>Alum Rock Youth Center, San Jose, California (2002)</td>
<td>BOORA Architects</td>
<td>Sawtooth roof monitors with forward tilted glazing areas facing south-east</td>
<td>Overhangs and side protection, windows are tilted forward to prevent beam light entering the building. Sunpatches can be observed on the gymnasium floor in some special times a year.</td>
</tr>
<tr>
<td>The Setubal College of Education Gymnasium, Setubal, Portugal (1993)</td>
<td>Alvaro Siza</td>
<td>Z-shaped roof monitors with forward tilted glazing areas facing south-east</td>
<td>Overhangs and side protection, windows are tilted forward to prevent beam light entering the building. Sunpatches can be observed on the gymnasium floor in some special times a year.</td>
</tr>
<tr>
<td>Lord's Cricket School, Marylebone Cricket Club, (MMC), London, UK (1995)</td>
<td>David Morley Architects</td>
<td>Integrated roofing system composed of curves with two separate sides. The south-facing side is opaque, whereas the north-facing side is transparent to receive diffuse light.</td>
<td>Interior fabric baffles to reject beam light. These baffles redirect light towards the roof and adds to the diffused light entering the space.</td>
</tr>
<tr>
<td>Yesler Community Center, Seattle, Washington</td>
<td>Foster and Partners</td>
<td>North facing roof monitors</td>
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</tr>
<tr>
<td>Stansted Air Terminal, Stansted, UK (1991)</td>
<td>Foster and Partners</td>
<td>Horizontal apertures in the middle of structural domes</td>
<td>Perforated metal sheet as diffusers</td>
</tr>
<tr>
<td>Airport Terminal Stuttgart</td>
<td>Von Gerkan / Marg</td>
<td>Localized apertures (square skylights)</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Architect</td>
<td>Daylighting System</td>
<td>Daylighting Control System</td>
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<tr>
<td>Harmony Library, Fort Collins, Colorado (1998)</td>
<td>David partnership P.C., Architects</td>
<td>Daylighting system: linear clerestory windows facing north and south</td>
<td>Daylighting Control System: overhangs on south side</td>
</tr>
<tr>
<td>The Academic Bookshop, Helsinki, Finland (1969)</td>
<td>Alvar Aalto</td>
<td>Daylighting system: prism-shaped skylights</td>
<td>Daylighting Control System: Interior pyramidal diffusers</td>
</tr>
<tr>
<td>The Viipuri Library, Vyborg, Russia (1935)</td>
<td>Alvar Aalto</td>
<td>Daylighting system: conical funnel-like horizontal apertures</td>
<td>Daylighting Control System: diffuse glazing</td>
</tr>
<tr>
<td>Smith Middle School, Chapel Hill, North Carolina (2001)</td>
<td>Corley Redfoot Zack, Inc. (Daylighting design: Innovative Design)</td>
<td>Daylighting system: Sawtooth roofs</td>
<td>Daylighting Control System: translucent fabric baffles</td>
</tr>
<tr>
<td>McPherson Middle School, Clyde, Ohio (2010?)</td>
<td>FHAI Designer: John McCreery</td>
<td>Daylighting system: Sawtooth roof</td>
<td>Daylighting Control System: fabric baffles</td>
</tr>
<tr>
<td>Location</td>
<td>Architect/Engineer</td>
<td>Daylighting System</td>
<td>Daylighting Control System</td>
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<tr>
<td>Arup Campus Office, Solihull, England</td>
<td>Architect: Arup Associates Daylighting system: lighting units designed to capture diffuse north light through an opening towards north and to control south direct light via louvers designed for the units’ south surface.</td>
<td></td>
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<tr>
<td>IDeAs office Building, Santa Clara, California (2007)</td>
<td>Architect: EHDD Architecture Daylighting system: Skylights (tilted by low angles)</td>
<td></td>
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<tr>
<td>Gothenburg Law Court Extension, Gothenburg, Sweden (1937)</td>
<td>Architect: Gunnar Aspuland Daylighting system: one large linear sawtooth aperture facing south for brightening the central Great Hall Daylighting Control System: Climate: Mild climate Notes: large south facing windows and clerestories could lead to savings in heating energy if night insulation was employed. In addition, no automatic lighting controls exist to respond to natural light. Therefore, this building fails to save energy through its daylighting strategy.</td>
<td></td>
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<tr>
<td>Metropoli Fundation Building, Madrid, Spain</td>
<td>Architect: Angel de Diego Rica</td>
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</table>
Lessons Learned From Case Studies

Rooflighting has a long history in museums because of the aesthetic features of light in space. Not only museums, but also other buildings such as airports, terminals, and monumental buildings were designed with daylighting ideas to create a pleasant space for visitors. Case studies indicate that during the last decades, other building types such as schools, offices and retail stores have implemented daylighting ideas for energy saving reasons. In fact, the purpose of daylighting in building has changed from solely aesthetic reasons to comfort and energy conservation goals. However, museums are still avant-garde in the field of rooflighting systems design. Moreover, financial issues are crucial, differentiating some building types with national importance such as museums from other building types.

There is not a specific configuration of roof daylighting system associated with a specific building type. Some configurations are more energy efficient that others, therefore, they are more widely employed in buildings with concerns about building operation costs, such as offices.

Buildings could be categorized in terms of lighting based on their scale and type of use. Daylighting in buildings with high ceilings such as airports differ significantly from buildings with low ceilings such as office buildings. Length of occupants’ stay in the building, their visual task, and their choice of seats in a space are important factors in daylighting design. Subtle and even lighting is required in spaces such as offices, in which people stay for long hours. On the hand, direct light is appreciated in spaces with recreational or leisure purposes due to dynamic character that beam sunlight creates.

In sunny locations, the issue of daylighting control becomes more important than locations with overcast sky conditions. In high latitudes, there are specific problems for daylighting. In such locations, south-facing clerestories with appropriate overhangs are more appropriate than horizontal roof glazings. For such solar altitude angles, daylighting strategies such as using prisms to redirect light into the space are used. There is also a lot of shading from neighbors or other obstructions because of very low solar altitude angle in such locations.

Simples systems often have higher level of performance. Most systems with additional surfaces, even if reflective, tend to globally decrease daylight penetration through the reduction of the solid angle of light collection and adding additional light absorptions in process. Complex systems involving highly reflective surfaces have performances that are very dependent on maintenance and durability of the
components. Dust, condensation or surface deterioration quickly reduces optical efficiency, sometimes by more than 50%.

In roof daylighting systems, function of space is crucial in evaluation of performance of the system. Some spaces perform well with rather low levels of light or even with direct sunlight hitting surfaces. As an example, circulation spaces do not have high illuminance requirement. Even the daylighting systems that substantially reduce the available illumination provide satisfactory level of performance for such spaces.

Secondary daylit spaces illuminated by atria do not often perform well in terms of efficiency. The reason is associated with the low level of daylight redirected to the secondary daylit spaces. In general, atria are not efficient daylighting ideas despite being architecturally pleasing. In addition to atria, there are other examples of buffer spaces designed for daylighting purposes. In some daylit buildings, a large area of a building is only dedicated for equalizing direct sunlight. However, in contemporary architecture and particularly in commercial buildings in locations with high real estate market, even a square feet of space becomes so valuable that its allocation solely for daylighting purposes is no longer appreciated.

Nowadays, increasing use of computer monitors necessitates the issue of luminance control inside buildings. Rooms with lower illumination are more appreciated to perform computer tasks. As a consequence, the required illuminance has been reduced in office spaces as the visual task has transformed from paper-based work to computer-based work.

This section discussed the lessons learned from cases studies of roof daylighting including some issues related to performance of such design strategies. In the next section, performance of daylighting systems will be discussed in more details.

2.1.3. Daylighting Systems Performance

Performance is a building criterion that stems from human needs. Building “performance” is divided into six categories (Hartkopf et al., 1986): visual performance, thermal performance, spatial performance, indoor air quality, acoustical performance and building integrity.

Visual performance is related to ambient and task levels, artificial light and daylight, contract and brightness glare, color renditions, view/visual information and occupancy factors and controls;
thermal performance in buildings depends on four design factors and all four of these elements constituting our thermal environment contribute significantly to our sense of comfort; spatial performance includes the design of individual spaces and their furnishing to provide the best support for the individual activity; indoor air quality is defined by providing fresh air, fresh air movement and distribution in a space; acoustical performance is related to Sound Sources, Sound Paths and Sound Receiver and building integrity corresponds to building loads, moisture, temperature, air movement, radiation and light, chemical attack, biological attack, fire, natural disaster and man-made disaster (Hartkopf et al. 1986).

Each of these performance mandates is defined by physiological, psychological, sociological, and economic needs or design limits of acceptability. The first five mandates relates to interior occupants of a building (human, animal, plant, and artifact occupancies) and health, safety and well-being of them in relation to spatial quality, thermal, air, acoustical and visual quality.

The last item, building integrity, relates to the building itself and concerns physical protection of the building’s appearance and its durability against moisture, temperature, air movement, radiation, chemical and biological attack and environmental disaster such as fire, flood, and earthquake.

Performance evaluation of a daylighting system is defined based on definition of a properly designed daylit space. A daylit space is defined as “a space that is primary lit with natural light and that combines a high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling (Reinhart, 2010)”. This definition highlights importance of visual and thermal performance in evaluation of daylighting systems.

Studying visual performance includes both quantity and quality of daylight. In addition to thermal comfort, which is the main goal in evaluation of thermal performance in buildings, energy-efficiency should be considered. Providing comfort with excessive use of energy is unreasonable and unjustified in the current era. In this section, daylight quantity, daylight quality, thermal comfort and energy efficiency will be explained as four main components for performance evaluation of daylighting design.

2.1.3.1. Daylight Quantity

The first goal in daylighting is to provide adequate quantities of natural light on task surfaces within the space. Contrast sensitivity of the eye, visual acuity and visual performance are important parameters to provide decent condition for a visual task. These three terms are measures of the same
stimulus-response relationship and when the three items provided together, a good measure of the
efficiency of the visual process will be achieved (Szokolay, 2008).

Contrast sensitivity of the eye is a characteristic of the eye, which is very good in good lighting. In
full daylight a luminance difference between surfaces as little as 1% can be distinguished but under
poor lighting conditions surfaces with up to 10% luminance difference may be perceived as equal. In
other words, light levels should be enough to distinguish luminance differences.

Visual acuity, or sharpness of vision depends on illuminance. Acuity is measured by the smallest
detail perceived, expressed as the reciprocal of the visual angle subtended at the eye by opposite
extremes of the least perceptible detail.

Visual performance is a function of time required to see an object, or of the number of items
perceived in unit time. The time required to perform a certain visual task decreases with the increase
of illuminance.

2.1.3.2. Daylight Quality and Visual Comfort

The second goal in daylighting design is to provide a visually comfortable space for all the common
tasks to be performed (Baker, 2002). The concept of quality with respect to daylight is primarily
concerned with the distribution of light at the point of interest. It is also concerned with the
distribution of the brightness of surfaces not just those of the task or object of interest, but also the
surrounding surfaces, the view of which contribute to a person’s overall perception of the space and
satisfaction from it (Baker, 2002). The brightness of a surface is a product of the illuminance and
reflectance of the surface.

Glare is a subjective human sensation that creates visual discomfort in a space. Glare is defines as
‘light within the field of vision that is brighter than the brightness to which the eyes are adapted’
(Baker, 2002). Two categories of glare have been identified depending on the magnitude of glare:
disability glare, and discomfort glare. Disability glare relates to inability of a person to see certain
objects in a scene due to oversupply of light, and discomfort glare relates to the premature tiring of
the eyes because of existence of glare. Discomfort glare is harder to identify because it is sensitive to
subjective opinion and linked to a person’s overall satisfaction of indoor environment (Szokolay,
2008, Reinhart and Wienold, 2010).
Discovery of acceptable limits of discomfort glare has been a topic of research for many years. There is a widely consensus that discomfort glare is related to luminance distribution in the field of view of an observer rather than illuminance distribution at task surface.

Acceptable level of light variation in field of view has been a debatable issue in the history of daylighting research. Although low level of light variation in the filed view is required to perform a visual task, human beings appreciate brightness contrasts between surfaces. Occupants seem to be more interested in the visual diversity of their surroundings rather than monotonous built environment. This raises an important issue in the discussion on contrast and temporal diversity in architecture.

In a study by Slater and Boyce (1990), participants were asked to rate the evenness of the lighting, its acceptability, and its comfort, in relation to various illuminance ratios across a desktop task. It was concluded that for tasks that are primarily in the center of the desk, illuminance ratios as low as 0.5 would be acceptable for most people (Slater and Boyce 1990, Veitch 2001). In a study conducted on the relationship between luminance diversity and the perceived quality of interior space (Steane and Steemers, 2004), "The more diverse the luminance in the field of view, the more 'pleasant', 'cheerful', 'bright', 'radiant', 'clear', 'visually warm', and 'strong' the space was reported to appear." In the same study, it was stated that subject desired to have diversity within their field of view and that was not related to inadequate illuminance levels. Although our codes and recommendations are concerned with task-based illuminance levels, occupants seem to be more interested in the visual diversity of their surroundings, establishing a need for new metrics that can quantify and place value in perceptual qualities.

Baker and Steemers (2002) indicate that daylight quality is influenced by both quantifiable and non-quantifiable parameters as perceived by the subjects based on a research carried out at the Martin Center, University of Cambridge. Subjects were willing to have non-uniformity in their surroundings but not so much between the average of their surroundings and their task. This variation could create visual interest as well as luminance variation.

Cuttle (2008) expresses results from an exercise he did in numerous occasions with his students inspired from J.A. Lynes (1987). In this exercise, he asked students about noticeable difference of brightness they perceived while looking at a white source of light mounted on a vertical surface.
Based on his observation, Cuttle concludes that illuminance differences lower than 1.5:1 are perceived as uniform lighting.

2.1.3.3. Thermal Comfort

The sensation of thermal comfort in a space depends on environmental factors: air temperature, mean radiant temperature, relative air velocity, and water vapor pressure in ambient air and physiological factors: skin temperature, core or internal temperature, sweat rate, skin wettedness, and thermal conductance between the core and skin (US DOE 2010). Providing thermal comfort is one of the key goals for daylighting design. Large glazing areas could result in large heat transfer via conductance and solar radiation.

2.1.3.4. Energy Efficiency

Energy efficiency is described as using less energy to produce the same amount of services or useful output. The third goal in daylighting is to reduce lighting electricity consumption and heating load from electric lights by switching off or dimming lights in response to the presence of daylight in a space. The purpose is to replace electric lighting by daylight without increasing heating and cooling loads in a building. In daylighting systems, excessive heat gains through the glazing area contribute to extra cooling energy consumption in cooling seasons. Furthermore, heat losses through the glazing and frames contribute to additional heating energy requirement in heating seasons. In a properly designed daylighting system, the advantages of reduced electric lighting due to daylighting overcome the disadvantages of increased conductive heat loss and increased solar heat gain through the glazing material.

In order to conduct accurate energy analysis in buildings, simulations based on hourly local weather data are required to estimate annual daylight availability and building energy use. Moreover, the effects that daylighting has on reducing electric lights and the associated internal heat gains should be accurately calculated.

2.1.4. Daylighting Performance Metrics

Now that four performance categories for daylighting performance have been defined, this section reviews a series of metrics that can be used to evaluate performance of daylighting systems.
2.1.4.1. Daylight Quantity

_Illuminance (E)_

Illuminance is the measure of illumination of a surface with the unit of lux (lx). One lux is the illuminance caused by one lumen incident of one square meter area (Tregenza and Wilson 2011). The physiological limits of accessibility and codes for lighting design are determined by the capabilities of the human eye, given tasks of specific size and contrast. The Illuminating Engineering Society (IES) defines the recommended levels of illuminance for various spaces. Recommended or prescribed illuminance values depend on the visual task, occupants’ age, socio-cultural and economic factor (Szokolay, 2008). Illuminating Engineering Society of North America (IESNA) requires Illuminance level of 200 lux for incidental (secondary) use, 300 lux for general office use, 500-700 lux for task lighting, and 1000 to 1500 lux for highly specialized work such as sewing, color comprehension, or electronic assembly.

_Daylight factor (DF)_

Daylight factor is the ratio of the indoor illuminance at a point to the outdoor horizontal illuminance, measured under CIE overcast reference sky conditions. Since DF is evaluated under a fixed sky condition that does not change according to the building location or orientation, it is considered a static daylight metric (Reinhart, et. al. 2010).

_Daylight autonomy (DA)_

Daylight autonomy is defined as the ratio of the total number of hours in the year when the minimum design illuminance is provided by daylighting alone, to the total number of hours of occupancy in a year. As apposed to static daylight factor, daylight autonomy is a dynamic daylighting performance metric because it is derived from models of real sky conditions at each sampling interval throughout the year, rather than on a fixed CIE Overcast sky, which is used for the daylight factor (Reinhart, et. al. 2010). DA metric uses the target illuminance for a space according to IESNA requirements (IESNA 2000) to identify the required level of lighting in a space.

_Useful daylight illuminance (UDI)_

Useful daylight illuminance is a dynamic daylighting metric that is defined as the ratio of the total number of hours in the year when useful illuminance is provided by daylighting alone (useful range is typically defined as 100 lux minimum to 2000 lux maximum), to the total number of occupied hours per year. The UDI is typically reported for three separate ranges of illuminance: UDI<100 lux, UDI
(100-2000lux), and UDI>2000lux (Reinhart et al., 2006). The upper bin (UDI>2000lux) represent
times when an overflow of daylight might lead to visual and/or thermal discomfort in a space, the
lower bin (UDI<100lux) characterizes times when there is ‘too little’ daylight available in a space and
the intermediate bin (UDI100-2000lux) represents ‘useful’ daylight which provides sufficient
illumination and visual comfort in a space (Reinhart and Wienold, 2010).

2.1.4.2. Daylight Quality and Visual Comfort

Luminance ($L$)
Luminance is reflected and transmitted light of a material or task level in a given direction and it is
measured in candela per square meter (cd/m$^2$) in SI unit. The light leaving the surface can be due to
reflection, transmission, and/or emission (Tregenza and Wilson 2011).

Luminance ratio
Some literature relate luminance ratio with human satisfaction with daylighting in luminous
environment. A general rule is that the luminance in a cone of 60° about the line of sight should not
exceed three times or be less than one third of the luminance of the main visual task. The luminance
in a cone of 120° should not exceed 10 times or be less than a tenth of the luminance of the main
visual task (IESNA 2000, CIBSE 1994). In short, the luminance ratios recommended are 1:3:10 in
“task: field of work: Environment” (Szokolay, 2008).

However, a universal criterion of good lighting probably does not exist, and even when considering a
single region, it is hard to find an obvious rule that guarantees good quality of lighting (Tregenza,
2011).

Vertical-to-Horizontal (VH) illuminance ratio
In order to characterize daylighting in an environment, some researchers focused on three-
dimensional illuminance distribution at a point in space. Love and Navvab highlighted the importance
of vertical illuminance and expressed significant contribution of reflected light from vertical planes
on horizontal task illumination (Love & Navvab, 1994). The researchers suggested Vertical-to-
Horizontal (VH) ratio at a point of interest as a complementary performance indicator of daylighting
systems in sunny conditions, where daylight factor becomes unresponsive. The VH ratios were
measured in a sidelite test room at three points with minimum, middle and maximum distance from the
window. It was concluded that the VH ratio could provide information on the presence or absence of direct sun, glare, contrast, and the balance of daylight illumination in a space.

*Cubic illumination*

Cuttle did one of the first attempts to reach a three-dimensional daylight measurement by proposing the concept of Cubic Illumination (Cuttle 1997). Cubic illumination defines the spatial distribution of illumination about a point in terms of the illuminance on six faces of a small cube centered at a point (figure 3). Cubic illumination was used in Cuttle’s study for arithmetical calculation of two components of light: vector and symmetric components, with the purpose of predicting the illuminance of a plane normal to the view direction at a point in space.

![Figure 3. Cubic Illumination](image)

*Daylight glare index (DGI), Daylight glare probability (DGP)*

DGI and DGP are metrics to measure discomfort glare in a space by mathematical formula driven from studies on human subject. The difference between DGI and DGP is in accuracy of estimation of luminous intensity from a source of glare. Daylight glare index is an equation driven from experiments with artificial glare sources under controlled simulated conditions rather than real sky conditions (Wienold and Christoffersen, 2006). Daylight glare probability (DGP) is a more recent metric proposed for measuring glare driven by laboratory studies in daylit spaces using seventy-two test subjects in Denmark and Germany (Wienold and Christoffersen, 2006).

DGP is defined by the following equation:

\[
DGP = 5.87 \times 10^{-5} \times E_{v} + 9.18 \times 10^{-5} \times \log \left[ 1 + \sum \left( \frac{L_{n,i} \omega_{n,i}}{E_{v}^{1.87} P_{i}^{3}} \right) \right]
\]  
(Equ1)
E_v: vertical eye illuminance
L_s,i: luminance of source i
ω_s,i: solid angle of source i
P: position index, a weighing function that varies with the distance of a glare source form the field of vision.

Wienold extended subjective studies to discover levels of acceptability of DGP (Wienold, 2009). Discomfort glare is divided into four ranges based on magnitude of glare and impairment of visual sense caused by glare. DGPs associated with subjective rating of glare were recorded and published in a graph (figure 4). The four categories include: imperceptible glare (DGP<35), perceptible glare (35<DGP<40), disturbing glare (40<DGP<45), and intolerable glare (DGP>45) (Reinhart and Wienold, 2010).

![Figure 4 Subjective visual sensations of DGP ranges (Source: Reinhart and Wienold 2010)](image)

2.1.4.3. Energy Efficiency

Technologies to harvest renewable energy such as solar energy and wind power reduce the overall use of fossil fuel in buildings. The goal is to design low-energy buildings to minimize the energy demand at first hand; to lessen the energy consumed to provide comfort condition for occupants, energy efficient buildings utilize highly efficient HVAC and lighting technologies. Net-zero energy buildings are examples of highly efficient buildings, whereby the amount of energy provided by on-site renewable energy sources is equal to the amount of energy consumed by the building. With decrease of the costs of alternative energy technologies, the zero-energy goal is becoming more practical nowadays.
Energy Use intensity (EUI)

Energy use intensity is a unit of measurement that represents energy use in buildings. EUI is the energy use per unit of floor area per year in units of \([\text{kBtu/ft}^2/\text{yr}]\) or \([\text{kWh/m}^2/\text{yr}]\) and it is the most commonly accepted metric to measure a building’s absolute energy use performance (ASHRAE 2010). Judgement of energy efficiency of buildings is made based on comparison of EUI between similar types of buildings and reduction of EUI in a single building.

Building Operation Costs

Building operation costs is the sum of annual costs of energy for building operation in units of dollars. Operation costs could be also presented in each unit of floor area \([\text{dollars/ft}^2]\) or \([\text{dollars/m}^2]\).

2.1.4.4. Thermal Comfort

The physiological limits of acceptable thermal performance for human occupancy in building have been well established, and documented in ASHRAE (American Society of Heating, Refrigerating and Air conditioning Engineers) Standards, Thermal Environmental Conditions for Human Occupancy. This standard, in turn, has been adopted by BOCA (the Building Officials and Code Administrators International), by state and local codes, and by numerous international codes (Rush, 1986). ASHRAE establishes the high and low limits of air and radiant temperatures, humidity levels, and air speeds within spaces in accordance with metabolic rates (activity levels) and clothing values, set by function and occupancy type. If well understood and followed by the building designer, it should ensure acceptable thermal conditions for 80 percent of the building occupants.

Mean Air Temperature \((T_a)\)

The average air temperature inside a room is defined as mean air temperature, which is one of the elements that affect thermal sensation of occupants in a space.

Mean Radiant Temperature \((T_r)\)

Mean radiant temperature was suggested to express the long-wave radiation energy received by the body when surrounding surface temperatures differ from the air temperature. Mean radiant temperature could have a significant influence on the heat loss from human body and thus on human comfort (Fanger, 1970).

There are two methods to calculate mean radiant temperature (US DOE 2010). First, mean temperature of surrounding surfaces is calculated and weighed according to the angle factor between
the occupant and surfaces. Second, a mean value of surface temperatures is calculated and weighed by their surface areas. In this method mean radiant temperature would be independent to the occupant’s location in a room. The second method is simplified and it has a wide range of application in practical engineering (Fanger, 1970).

**Operative Temperature**

To account for the effect of radiation on comfort sensation, operative temperature was suggested rather than mean air temperature to be measured in a space (Fanger, 1970, Arens et al. 1986). Operative temperature is a combination of mean air temperature and mean radiant temperature. Chapter 2.3 will provide more information.

Window surfaces inside a room may cause an occupant feel hot or cold despite a comfortable surrounding air temperature (Lyons et al. 2000). Occupants inside a room feels a different temperature, which is the combined effect of mean air temperature and mean radiant temperature based on ASHRAE Standard 2004 (ASHRAE 2004). This temperature is known as operative temperature ($T_o$).

In the two-node comfort model, operative temperature ($T_o$) is defined as the average of the mean radiant temperature and mean air temperature, weighted by their respective heat transfer coefficients (US DOE 2010).

$$T_o = (h_c T_a + h_r T_r)/(h_c + h_r)$$

Operative Temperature = (Hc*AirTemp + Hr*RadTemp)/h

$$h = h_c + h_r$$

$$h_c=8.3\sqrt{v}$$

$$h_r=3.87+0.031 T_r$$

$T_o$: Operative Temperature

$T_a$: Mean Air Temperature

$T_r$: Mean Radiant Temperature

$h_c$: the convective heat transfer coefficient, which varies with the air velocity around body and metabolic rate.

$h_r$: the radiant heat transfer coefficient, which varies with $T_r$, mean radiant temperature.

In ASHRAE Standard 55-2004 (ASHRAE 2004, US DOE 2010), the following formula is suggested for operative temperature:
\[ T_o = \gamma T_r + (1-\gamma) T_a \]

\( T_o \): Operative Temperature  
\( T_a \): Mean Air Temperature  
\( T_r \): Mean Radiant Temperature  
\( \gamma \): radiative fraction  

Radiative fraction \((\gamma)\) is a constant value that depends on relative air velocity and can be determined based on Standard 55-2004 (ASHRAE 2004). A typical value of \( \gamma \) is 0.5, with maximum value of 0.9 and minimum value of 0.0. Value of 0 means that the operative temperature is similar to the mean air temperature. When air velocities are higher than 0.2 m/s, then lower values for radiative fraction might be used.

ASHRAE 55-2010 defines acceptable range of operative temperature and air speed for the comfort zone, depicted in figure 5.

\[\text{Figure 5 Acceptable ranges of operative temperature and air speed for the comfort zone (ASHRAE 55-2010).}\]

The thermostat control in conventional HVAC systems is based on mean air temperature measured by a sensor placed in the return air path. However, this method ignores the radiant temperature felt by occupants inside a room with windows. When they feel hot or cold, occupants would manipulate the thermostat settings to reach a state of comfort. This behavior impacts energy consumption, which is not considered in energy simulations based on mean air temperature set points. Therefore, accurate
energy consumption would not be reported due to differences in real condition that the simulation inputs.

Nu and Burnett (1998) has first investigated the variations in thermal loads and energy consumption when operative temperature was used as a set point versus mean air temperature. These researches reported an increase in heating load in various office buildings when thermostat operative temperature was compared with mean air temperature (Nu and Burnett 1998, Caillet et al. 2009, Kumar 2011, Jain et al. 2011). However, variation is energy consumption depends on location, thermal properties of building envelope, area and distance of radiating surfaces, such as windows, and internal surfaces (Jain et al. 2011).

Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are two indices to predict the occupants’ thermal sensation and specify acceptable thermal condition for an environment. PMV and PPD are used in the international Standard ISO 7730 (ISO, 2005) and they were originally proposed in Fanger’s model, which is the most famous model of thermal comfort (see chapter 2.2.3). Predicted Mean Vote is a thermal sensation scale generated based on the following formula:

\[
PMV = (0.303e^{-0.036M} + 0.028) (H - L)
\]

H: Internal heat production rate of an occupant per unit area (= M – W)
L: Energy loss from the body

2.1.5. Roof Daylighting Systems Performance

“Skylights” are the most popular rooflighting system in some building functions such as warehouses and retail stores. It is important to explore if skylights perform in an energy efficient way and investigate design issues that contribute to inefficiency of skylights. Performance of all rooflighting systems depends on sky conditions simply because they are directly facing the zenith. Likewise, performance of skylights is related to sky conditions. Therefore, to judge performance of a skylight, daylighting condition of that specific location should be studied at first.

Most skylights are implemented with a diffuse glazing material or a diffuser plate underneath to equalize outside daylighting conditions. This daylighting control system is a conventional strategy to control beam sunlight due to its ease of application and low cost. In a skylight system tested by
Heschong Mahone Group (2004), the Effective Visual Transmittance (EVT) decreased by 23% when a diffuser with 86% light transmittance replaced a clear glass in the skylight.

One of the evident flaws of conventional roof-lighting systems is “glare”. By choosing the right material, glare problems of diffused skylights can be resolved. Different materials have various levels of “haze” indicating their ability to diffuse direct sun light. By choosing the ones with higher haze values, the glare problem is resolved. For example, white Acrylic with 100% haze can achieve complete diffuse of light. “Haze values above 90% describe glazing materials that are essentially diffusing” (McHugh et. al 2004).

However, choosing the “right” diffuse material that could resolve glare problems without reducing light transmittance significantly is challenging. Producing a perfect diffuse glazing material with high level of visible transmittance has not been fully accomplished in glass industry. As a result, using diffusers in rooflighting systems reduces the light transmittance levels and reduce efficiency of the systems.

Increasing the number of skylights might appeal as a solution to increase daylight illumination in spaces with skylights. However, increasing the number of skylights means increasing conductive heat transfer through the roof, reducing R-value of the roof and waste of energy. R-values required for ceilings, according to 2006 IECC (International Energy Conservation Code), are 30 [hr.°F/Btu] in hot climates, 38 [hr.°F/Btu] in mixed hot and cold, and 49 [hr.°F/Btu] in cold and very cold climates. Therefore, increasing the number of skylights is worse for northern states of America, where higher R-values are required for ceilings. Cost is another issue to consider when increasing the number of skylights. Increased cost of adding skylights doesn’t make up for the benefits of saving energy in many cases.

Apart from adverse effect of diffusing light in skylights, there are other problems with skylights, which reduce their performance for rooflighting. Light well is the other major problem of skylights. A study by McHugh shows that the Effective visible transmittance is reduced on average by 28% when light well height is increased from 1’ to 3’ tall. EVT is reduced on average by 56% from 1’ to a 6’ tall light well (McHugh et al. 2004).

In a report by Tyson Lawrence and Kurt W. Roth for the U.S. Department of Energy in 2008, many issues about skylights are discussed. The goal of this paper was to give an estimate of toplighting
energy saving potential and to review possible actions that can accelerate the market adoption of toplighting. This study focuses on the relationship between cost and energy savings.

However, only a small fraction (2-5%) of commercial building floor space has currently utilized skylights for daylighting because of limitations of skylights. The Key limitation of skylights is known as high levels of costs compared to their energy benefits. The other limitations are introduced as inadequate knowledge and awareness about skylights daylighting performance, leakage from skylights and complications with daylight controls systems. It is interesting to know that building owners usually do not consider skylights without lighting controls to be an attractive investment (Lawrence & Roth, 2008).

Commercial buildings could be divided into two main categories based on the patterns discovered from the findings (Lawrence & Roth, 2008):

- Buildings with high open ceilings such as warehouses and big retail stores
- Buildings with lower drop ceilings such as offices and schools where light wells are required.

Studies show that energy savings of skylights are higher in the first category than the second category with the same area of skylight (Heschong Mahone, 2008). The payback period calculated for energy effects only range from four to ten years in the first group of buildings with high ceilings, while it ranges from 30 to 40 years in the second group with lower ceilings with light-wells (Lawrence & Roth, 2008). Reasons include having lower light level requirements in warehouses than offices due to their task and it could be because having more uniform light in higher ceilings. In addition, the long payback period is associated with existence of light-wells, which significantly lower daylighting performance of skylights.

In the latest report by Heshong Mahone Group, called “skylights requirement code change proposal” submitted in 2008, savings from skylights are estimated. In this analysis, the ratio of benefits to costs of skylights is found for all climate zones for two building types: warehouses (with 32ft and 24ft ceiling) and retail stores. Skylight to floor area ratio (SFR) of 3% was chosen for the Retail and warehouses. But offices need higher effective aperture or greater SFRs to save energy as much as warehouses with skylights do (Heshong Mahone, 2008). For office buildings, it is reported that effective apertures greater than 0.6% still allow cost-effective savings in most climate zones except for climate zone 8. Saving more than $0.066/sf.yr were investigated for skylighting systems with effective apertures greater than 0.6% (0.006) for most climate zones (Heshong Mahone, 2008).
It should be pointed out that in both reports by Lawrence and Roth and Heshong Mahone group, “Toplighting” is defined as roofing systems with skylights. Thus, these reports do not include information about other daylight roofing systems such as roof monitors. The methodology that authors followed was simulation by SkyCalcTM. However, SkyCalc does not provide an accurate daylighting simulation (it will be discussed in lighting simulation chapter).

Due to low daylighting performance of skylights in office buildings, researchers conclude that it is required to suggest new design for skylights to solve their problem. However, none of the existing studies investigated design improvement options to increase performance of skylights. Only sloping the light-wells was introduced as the only design modification by Heshong Mahone (2003) for retail stores.

The optimum SFR for retail and warehouses is known to be 3%. For offices larger SFRs are required to compensate for non-uniformity of lighting created in such spaces with low ceilings. Effective apertures more than 0.6% were suggested in the literature for most climate zones. However, increasing the SFR increases energy costs for heating and cooling purposes. Therefore, inquiring about that optimum SFR becomes a crucial task to pursue.

Problem with glare was not investigated for achievement of human visual comfort in spaces. Lawrence and Roth state that the higher the visible transmittance of skylights, the higher the level of performance. When visible transmittance is higher, lower total skylight area is required and lower thermal loss is generated (Lawrence & Roth, 2008). However, negative effects of glare are not explored.

2.2. BUILDING SIMULATION METHODOLOGIES
In this section, lighting simulation and energy simulation will first be discussed. Afterwards, models of predicting thermal comfort will be illustrated; finally, comparison between simulation methods will be made followed by the conclusions.

2.2.1. Lighting Simulation

Lighting simulation algorithms, simulation types, electric lighting control system modeling, lighting simulation tools, and accuracy of lighting simulation will be discussed in this section.
2.2.1.1. Lighting simulation Algorithms

*Split-flux*

In Split-flux method, the daylight transmitted by the window is split into two parts: (1) a downward traveling flux, which falls on the floor and portions of the walls below the imaginary horizontal plane passing through the center of the window; and (2) an upward traveling flux that strikes the ceiling and portions of the walls above the window midplane. A fraction of the flux is absorbed by the room surfaces (Guglielmetti and Scheib, 2012).

Split-flux method calculates the effects of (critical) interreflections within an interior space (Winkelmann, 1983, Guglielmetti and Scheib, 2012). This component is the contribution of all the ambient illumination that is the result of direct luminous flux from the sun and sky being reflected by building surfaces and local terrain, and distributed to other areas in the space. This indirect or reflected component can contribute significantly to the total illumination, particularly when light-redirecting devices (e.g., lightshelves) are used.

This method has the disadvantage of assigning one reflectance value throughout interior surface areas. In fact, it assumes an evenly distributed interreflected light throughout a space by using area weighted average surface reflectance values for upper (i.e., ceiling and upper wall) and lower (i.e., floor and lower wall) surfaces within the space (Winkelmann, 1983).

DOE-2 and early version of DElight (v.1-1.5) used the split-flux algorithm for lighting simulation (Winkelmann, 1983). Winkelmann explains a detailed description of the Split-flux algorithm within the DOE-2 but the three major steps include (Winkelmann, 1983):

1. **Daylight factor preprocessor:** interior illuminance at user-selected room locations is calculated for a standard overcast sky and for clear sky conditions with 20 different sun positions. Dividing the interior illuminance by the corresponding exterior illuminance gives daylight factors, which are stored for a later interpolation in the hourly simulation. The interior illuminance calculation accounts for the luminance distribution of the sky, window size, slope and orientation, glass transmittance, inside surface reflectances, sun control devices such as drapes and overhangs, and external obstructions.

2. **Hourly daylight simulation:** the hourly illuminance and glare contribution from each window is found by interpolating the stored daylight factors using the current-hour sun position and
cloud cover, then multiplying by the current-hour exterior horizontal illuminance. Back then, this process of interpolating pre-calculated daylight factors to obtain hourly illuminance and glare reduced computation time by a factor of 200 compared to hourly calculations considering the equipment at the time.

3. Hourly lighting control simulation: stepped and continuously dimming lighting control systems are simulated to determine the electrical lighting energy needed to make up the difference between the daylighting level and the design illuminance. Finally, the lighting electrical requirements were passed to the thermal calculation, which determines hourly heating and cooling requirements for each space and for the building as a whole.

Validation of DOE.2 has been undertaken by comparing the results of DOE.2 and SUPERLITE with a scale model in LBL. The results include daylight factors in clear and overcast sky conditions for a small, single-occupant office model. The difference in the ratio of the three methods is generally less than 15% except very close or far from the window. The split-flux method overrates interreflectances in areas close or far from the windows.

Radiosity

Radiosity algorithm enhanced calculation of interreflected light inside models compared to split-flux method (Selkowitz et al., 1982). Specifically, radiosity method accounts for ambient lighting more accurately. In radiosity algorithm, assumption in the daylight modeling is that illumination at each point of interest is composed of three parts: 1) direct sky illumination, 2) illumination from external reflectors, and 3) illumination from internal reflectors such as walls.

In this simulation approach, a hemisphere, with a large radius, is placed around the scene and it is subdivided into smaller emitter patches. All sky patches are regarded as shooting patches. For each of 145 sky patches, luminance is computed and it acts as a light source in the illumination simulation process.

The surfaces of building model are also subdivided into smaller surfaces or patches. For each pair of patches, a view factor is defined. View factor is the flux that is received on the second patch when it leaves the first patch. Luminous flux is “shot” from the light sources to the scene, and the surfaces that receive direct illumination shoot their reflected energy back into the space, spreading smaller amounts of energy, until a significant amount of the initial flux (typically 98-99%) has been distributed into the space (Guglielmetti and Scheib, 2012).
Another advantage of Radiosity to Split-flux algorithm is simulating more than simple rectangular rooms including nonrectangular surfaces and other complex geometries such as L-shape room, a room with internal partition or external obstructions. In radiosity method, windows could have any generalized trapezoidal shape with arbitrary tilt angle. Overhangs or fins with opaque, translucent and semi-transmitting materials could also be modeled.

However, one limitation to radiosity is that Lambertian emission is assumed for all surfaces. In other words, it is assumed that all surfaces equally reflect light in all directions. Therefore, effects of light redirecting devices with specular and semispecular surfaces are neglected. Another limitation of radiosity algorithm is that mesh resolution is not completely controlled by the user (Guglielmetti and Scheib, 2012).

In addition, simulation of complex fenestration systems is not possible with radiosity algorithm. In order to make a significant enhancement, Bidirectional Transmittance Distribution Functions (BTDFs) were used in tools such as DElight 2.0 to overcome the problem (Hitchcock and Carroll, 2003, 2005). Therefore, radiosity method becomes too compute-intensive for most architectural daylighting applications and it is not well automated to fulfill needs for simulating a wide range of daylighting conditions e.g., reflective or light re-directive surfaces and complex geometries such as curved surfaces. Despite extensive research about radiosity approach for daylighting simulation, it has not been used to render a virtual scene or predict accurate daylighting illumination inside a building (Ward, 1994).

DElight 2.0, SUPERLITE, AGi32, and DIALux use radiosity algorithm for lighting simulation. Importance of DElight is because it is the main daylighting simulation engine used in EnergyPlus. DElight, first introduced in 2003 (Hitchcock and Carroll, 2003), has a heritage from several sources. Versions 1.x were based on Split-flux algorithm used in DOE-2 (Winkelmann, 1983). Version 2.0 of DElight enhanced the original version by replacing the previous method with the radiosity method. DElight was completely implemented, integrated with EnergyPlus and tested in 2005 (Carroll and Hitchcock, 2005).

The mathematical basis of the radiosity algorithm in SUPERLITE has been described in a paper published by the Lawrence Berkeley Lab (Modest et al. 1982). Major steps of the process are explained in this section:
1. **Sky luminance variation**: first sky luminance is defined by modeling the sky. Any sky model such as a uniform sky, CIE standard overcast sky, CIE standard clear skies with or without direct sun can be modeled.

2. **Geometric modeling of inside/outside surfaces**: geometric modeling is done based on mathematical equations that relate building parameters together.

3. **Determination of the luminance distribution on external surfaces**: the luminances of the ground, adjacent buildings and other external obstructions are calculated based on the luminance distribution of a given sky modeled at first step.

4. **Determination of the luminance distribution on internal surfaces**: the luminance across an interior surface may vary significantly, and this variation may profoundly affect the illuminance on the workplane. Thus, each surface will be divided into a number of sub-surfaces and the luminance of each sub-surface calculated separately. In an equation, directly transmitted luminance and diffuse transmitted luminance through clear or translucent glazing are added up together.

5. The amount of light flux transmitted from each glazing surface to the interior surfaces is calculated based on the luminance emanating from the first surface and the angle between the surface normal and the direction under consideration.

6. **Working surface illumination and daylight factor**: once the luminance of all interior and external surfaces has been calculated, the “imaginary working surface” is placed into the room and divided into a grid of nodal points. The illumination at any node in the room can be computed by integrating the surface luminances over the appropriate solid angles.

DElight 2.0 has developed algorithms for analyzing complex fenestrations systems (CFS) (Hitchcock and Carroll, 2003). BTDF for a Complicated Fenestration System (CFS) is a set of data that have been pre-calculated or pre-measured for a given CFS, which captures the ratios of incident to transmitted light for a range of incoming and outgoing directions. A CFS is regarded as a flat two-dimensional light-transmitting surface that is treated as an aperture surface in the room description. For each incoming direction across the exterior hemisphere of the CFS, it transmits varying portions of that light at multiple outgoing directions across the interior hemisphere of the CFS. The pre-calculated files are independent of the final position and orientation of the CFS aperture. Once a specific instance of a CFS aperture has been positioned within a building model, the incident light from all exterior sources across the exterior hemisphere must be integrated over all incident directions.
for each relevant transmitted direction to determine the light transmitted by the CFS surface. The
algorithms for the CFS treatment must be either measured or simulated prior to employing DElight to
analyze it within EnergyPlus. Until 2005, DElight supported two format to input BTDF files, by
analytical and file-based approach.

Validation of DElight 2.0 is examined by comparing measurements and simulations in a simple-
geometry text box for combinations of fenestration system and sky conditions. The light levels inside
a light-redirecting system under CIE overcast sky are measured and compared with simulation results.
Based on the aggregate RMS (Root Mean Square) difference of 10% between measured and
simulated results in that special case, it was concluded that the early results are promising and
DElight is suitable for doing quantitative estimates of performance of these systems for building
design purposes (Carroll and Hitchcock, 2005).

However, the validation results are disputable because the published result only relates to overcast
sky condition, which is the most stable and predictable condition. Besides, other complicated
fenestration systems, such as diffusive panels and roof monitors have not been studied. Maamari and
Anderson have conducted extensive study about validation of BTDF in terms of daylight performance
in 2005; that study provides a more comprehensive understanding about validation of BTDFs for
daylight simulation engines such as DElight2.

Light-backward Raytracing

Light-backward raytracing is a lighting algorithm implemented in RADIANCE. Radiance first
released in 1989, is a physically-based rendering system that uses ray-tracing method for creating a
real simulation of a daylit space (Ward, 1994).

In raytracing method, rays are traced from a viewpoint (or a calculation point) into the space, and
tested for intersection with the objects in the scene. Once the nearest object has been identified, the
algorithm will estimate the incoming light at the point of intersection, examine the material properties
of the object. If an object is a non-light source, more hemispherical rays are produced from that point,
back into the space to search for light sources (Ward, 1994, Guglielmetti and Scheib, 2012).

When a light source is intersected, the algorithm calculates luminous intensity of the source at that
intersection angle; this value is then reduced to account for bounces of light along the way from the
first calculation point to the final light source. To sample diffuse interreflection, Radiance also uses
hemispherical sampling at discrete points throughout the model and interpolates across these points for the ambient illumination (Guglielmetti and Scheib, 2012).

This method is called "backwards" raytracing since it sends rays away from the calculation point (receiver of light), rather than into it as actual light does in reality. Doing so is significantly more efficient as the overwhelming majority of light rays from a given light source do not make it directly into the viewer's eye. A "forward" simulation could potentially waste a tremendous amount of computation on light paths that are never recorded (Ward, 1994).

Radiance has been validated (Mardaljevic, 2000) and studied by numerous researchers and scientists. Several attempts have been made to provide graphical user interface (GUI)-based tools (e.g., Ecotect, Diva and OpenStudio) to make the tool more widely used.

2.2.1.2. Lighting Simulation Types

Now that lighting simulation algorithms, the tools that implement those algorithms, and potentials and limitations of tools are defined, it is time to describe simulation methodologies. This section is composed of --- parts: simulation type explains how the daylighting is simulated over time.

*Point-in-time Simulation*

The first method for simulating daylighting performance over time is to conduct a simulation for each timestep. In point-in-time simulation, a certain location, time, and sky condition should be defined. The aforementioned algorithms are applied, and results are saved. Point-in-time simulations are suitable to compare daylighting systems and investigate their performance at special time, day, or sky condition in a year.

For annual simulation, point-in-time simulations should be repeated for every daylit hour of a year. Conducting a full simulation in this method is computationally expensive, and impractical.

*Interpolated Design Day*

in this approach, several point-in-time simulations are performed for a number of key design days under overcast (CIE Type 1) and clear (CIE Type 12) sky conditions. Design days are typically four days: summer and winter solstice, fall and spring equinox. Interior illuminance and exterior global illumination is calculated at each timestep for the design days. For all other times of a year, outdoor global illumination is calculated with the use of weather data and compared to the nearest design day. Interior illuminance for each single time is calculated by applying a scaling factor to the illuminance
level received at the nearest design day. This scaling factor implements the difference in sky conditions of a non-design day from a design day. Although weather data is taken into account in this method, a fair bit of interpolation reduces accuracy of the illuminance data at points of interest.

_Daylight Coefficient (DC) Approach_

This method was first introduced by Tregenza and Waters (1983) and first implemented in DAYSIM tool by Reinhart and Jones (2000). In this approach, contribution of individual patches of a discrete luminous hemisphere in a building is calculated for a certain node. This process is similar to point-in-time simulation; contribution of each patch of the sky to illumination received at a certain point in a building with a desired geometry and properties is called Daylight Coefficients (DC). After calculation of DCs, a representative sky is generated for each timestep. The flux density in each patch is then multiplied by the previously calculated DCs to reflect the effects that geometry, materials and other building properties have on the received illuminance at a certain point in space. This process is repeated for all sky patches and summed for each time-step.

The benefit of Daylight Coefficient method is that DCs are calculated with accurate approach of raytracing, however, there is a limitation of approximating solar contribution. Further subdivision of the celestial hemisphere to 580 patches was proposed to substitute the original 145 patches of Tregenza (Bourgeois et al., 2008). This strategy was proved to improve accuracy of DC method (Ward, 2010).

2.2.1.3. Electric Lighting Control System Modeling

Proper simulation of electric lighting controls is a crucial factor in estimation of savings from daylighting systems. Most daylighting simulation tools assume an “Ideally commissioned” photosensor on the ceiling that responds directly proportional to illuminance at task surface (Guglielmetti and Scheib, 2012). EnergyPlus, DAYSIM and OpenStudio currently employ the same technique and simply calculate illuminance at a point on the task surface as an indicator of lighting photosensor signal.

However, in reality a photosensor on ceiling looks down at work plane and reads the illuminance. SPOT (Sensor Placement and Optimization Tool) is the only currently available tool that accounts for sensors’ spatial sensitivity. Developed by The Architectural Energy Corporation (2008), SPOT is capable to establish the optimal photosensor placement for a space. The general purpose of this stand-alone tool was to assist designers in identifying quality of lighting and daylighting in a space.
In fact, SPOT uses rsensor tool in Radiance to send a backward rays from the sensor on ceiling to account for this effect. However, this software is limited to simple geometries (Guglielmetti and Scheib, 2012).

The other key element in electric lighting control systems is the way electric lights are simulated. In simulation tools such as EnergyPlus, DAYSIM and OpenStudio, electric lights are regarded as a connected load, which is accustomed to the daylighting condition. To define various lighting groups, a percentage of the total load is assigned to a control point. This is called load-based electric lighting (Guglielmetti and Scheib, 2012).

2.2.1.4. Lighting Simulation Tools

This review is dedicated to daylighting simulation tools in building science; thus, simulation tools used for rendering or electric lighting design are excluded.

The United States Department of Energy (US DOE) provides an exhaustive list of various simulation tools to evaluate energy use and indoor comfort in buildings. The simulation tools are categorized based on subject, platform and country. Some of those tools are designed for lighting and optimization of electric lighting inside buildings and some others are specifically capable of handling daylighting simulation. The simulation tools designed for daylighting are Radiance, SuperLite, SPOT, AGI, Daylight, Building Design Advisor, ENER-WIN, CompuLyte, and AAMASKY.

A concise review of the current simulation tools for zero-energy buildings design is provided by Guglielmetti et al. (2010). Radiance, AGi32, Autodesk 3ds Max Design, Dialux, Relux are listed as capable tools with different algorithms to simulate and calculate daylighting in sophisticated geometries.

Ochoa et al. (2011) provides an extensive review of lighting simulation tools including Radiance, AGi32, DIALux, Relux, Inspirer, Lightscape, and Velux Daylight Visualizer. Table 1 summarizes the algorithms, purpose and availability of these lighting simulation tools (Ochoa et al. 2011).

From the list of all simulation tools provided, the most influential model among lighting simulation research and building science communities is Radiance (Ward, 1994, LBL, 2010a, Ochoa et al., 2011).
Table 2 Summary table of current lighting simulation tools (Source: Ochoa et al. 2011)

<table>
<thead>
<tr>
<th>Tool</th>
<th>Algorithm Used</th>
<th>Purpose</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGi32</td>
<td>Direct Calculation Radiosity Limited Raytracing</td>
<td>Luminaire Design</td>
<td>Paid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daylight Integration</td>
<td></td>
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<tr>
<td>DIALux</td>
<td>Direct Calculation Daylight Calculation</td>
<td>Luminaire Design</td>
<td>Free Proprietary Software</td>
</tr>
<tr>
<td></td>
<td>Pey Raytracen Images</td>
<td>Daylight Integration</td>
<td></td>
</tr>
<tr>
<td>Inspirer</td>
<td>Bidirectional Raytracing</td>
<td>General Purpose</td>
<td>Found within Paid Modeling Software</td>
</tr>
<tr>
<td>Mental Ray</td>
<td>Photon Map Radiosity Principles Raytracing Principles</td>
<td>General Purpose</td>
<td>Free</td>
</tr>
<tr>
<td>Radiance</td>
<td>Backward Raytracing Scene Radiance</td>
<td>General Purpose</td>
<td>Free Open Source</td>
</tr>
<tr>
<td>Relux</td>
<td>Direct Calculation Radiosity and Modified Radiance Raytracing</td>
<td>Luminaire Design</td>
<td>Free Proprietary Software</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daylight Integration</td>
<td></td>
</tr>
<tr>
<td>Velux Delight</td>
<td>Photo Map Bidirectional Raytracing Irradiance Caching</td>
<td>Conceptual Stages in Daylight Application</td>
<td>Free Proprietary Software</td>
</tr>
<tr>
<td>Visualizer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To highlight the influence, it is suffice to say that Ward’s conference paper (1994) was cited for 638 times according to Google Scholar and the book by Ward and Shakespeare (1998) has recorded 294 citations in the Scopus database (Ochoa et al., 2011).

Radiance has been one of the first tools that generated results for a fixed viewpoint by inserting the three-dimensional geometric data and physical properties of materials to explain the scene. Rather than rendering, Radiance is applied for building research, it is adjustable to solve most of simulation problems in natural and electrical lighting simulation, it is available for free and agreed to be distributed under open source agreement (Ochoa et al., 2011). In addition, Radiance is an extensively validated simulation tool with consistent accuracy within acceptable limits (e.g. Grynberg 1989; Mardaljevic 1995, 2001 and 2004; Ng 2001; Reinhart and Herkel, 2000; Reinhart and Walkenhorst 2001; Reinhart and Andersen 2006). Furthermore, Radiance has been the simulation engine incorporated with other tools such as ADELINE (FIBP 2002, discontinued support), Desktop Radiance (LBL 2000, discontinued support), Rayfront (Mischler 2003, discontinued support), Daysim(NRC 2009), and Radiance IES (IESVE 2010).
2.2.1.5. Accuracy Validations

Ochola et al. (2011) provide a comprehensive evaluation of lighting simulation tools. In this extensive literature review, validation and comparison of lighting simulation tools are categorized into two large groups: comparisons based on replicating a built reality, and comparisons in controlled laboratory settings.

Examination of physical models under real sky conditions is valuable to acknowledge architects and designers about natural occurrences in buildings. Validations of lighting simulation tools through natural physical experiments have been used to validate and compare lighting simulation tools (Roy 2000, Ubbelohde and Humann 1998, Ashmore and Richens 2001, Galasiu and Atif 2002, Ochoa and Capeluto 2006).

Lighting simulation tools have also been validated under controlled laboratory settings (Mardaljevic 1995, Khodulev and Kopylov 1996, Fontoynton et al. 1999, Reinhart and Walkenhorst 2001, Reinhart and Brenton 2009).

Each approach has benefits and limitations. Laboratory tests provide more control over the test conditions that could be replicated in simulation models. However, physical experiments are hard to replicate because the exact sky condition and surface reflectances could not be repeated in simulation models. Consequently, in literature review, accuracy of lighting simulation tools was reported at a higher level in laboratory tests rather than real condition tests (Ochola et al. 2011).

In lighting simulation field, no general consensus is yet achieved for defining the “acceptable” degree for accuracy in simulations. CIE (Fisher 1992) reported that the acceptable range of difference between measurement and simulation would be 10% for average illuminances and 20% for point values. Galasiu, Atif (2002), Reinhart and Anderson (2006) have validated accuracy of 20% for Radiance-based daylight simulation in indoor environments in real cases. It is indicated that the difference between simulated and measured values increase under direct sun (Galasiu and Atif, 2002).

Higher level of accuracy of two to seven percent is expected for validations under controlled conditions of laboratories. As an instance, Schregle and Wienold (2004) validated 7% and 2% differences in their study.
2.2.2. Energy Simulation

Lighting simulation is a single component of the whole-building simulation, where all influential factors on building operation are calculated. Calculation of the solar radiation transmitted through windows has been incorporated since the earliest whole-building simulation tools, such as DOE-2 (Reilly et al. 1995). However, other leading factors required for accurate daylighting simulation have been simplified in whole-building simulation tools. These factors include: modeling details in building geometry, accounting for sudden changes of daylight, calculating the exact light transmission through various glazing materials and fenestration systems, and modeling real electric lighting control systems. Although stand-alone lighting simulation tools are capable of modeling these complicated features to certain levels, whole-building energy simulation tools have maintained simplicity in this regard to reduce execution time (Ochola et al., 2011).

Energy calculations provide a basis to calculate the cost of building operation. There are two general methods for energy calculation: steady-state methods and dynamic methods. Steady-state methods such as degree-day method, variable based degree-day method and bin and modified bin methods assume a steady condition for calculations (Rizki et al., 2011). Dynamic method tries to account for dynamic response of buildings, usually on an hourly bases by computer simulation programs. Nowadays, most building energy simulation tools utilize the dynamic method.

The United States Department of Energy (US DOE) provides an exhaustive list of various energy simulation tools. Some examples of these tools are EnergyPlus, DOE-2, BLAST, ESP-r, Energy-10, and ENER-WIN.

2.2.2.1. Energy Simulation Tools

Existing tools for building performance simulation are compared in a study in 2011 (Attia and De Herde, 2011). The examined tools included HEED, e-Quest, ENERGY-10, Vasari, Solar Shoebox, Open Studio Plug-in, IES-VE- Ware, DesignBuilder, ECOTECT and BEopt. Metrics for evaluation of tools were composed of: 1) Usability and information management, 2) Intelligence and integration of knowledge-base, 3) interoperability, 4) process adaptability, and 5) accuracy. Although all the mentioned parameters have significant roles in choosing an appropriate tool for building performance evaluation, some parameters were valued higher than the others for the specific purpose of this study.

Accuracy is the first and foremost important criterion for this research, which involves complex geometrical configurations. Second, usability and flexibility of outputs from simulation is crucial for
allowing use in statistical analysis. Third, interoperability of the tool is crucial, as it facilitates the research process by allowing geometry exchange between various drawing tools.

EnergyPlus is the choice for this study to be used as the source engine for energy simulation because it is a validated program with high level of accuracy and wide range of application. EnergyPlus could be used with graphic user interface (GUI) for more convenient and faster modeling and interpretation of results (Crawley et al., 2004).

2.2.2.2. Integrated Whole-Building Simulation

Two approaches exist for incorporation of high quality lighting simulation methods with whole-building simulation tools:

- A discrete process, whereby two stand-alone simulation tools are used separately
- An integrated process, where a single program performs two separate engines for lighting and whole-building simulation

Studies have been conducted by using a discrete process (Koti and Addison, 2007, An and Mason, 2010) to incorporate a high quality lighting simulation with whole-building simulation tools. On the other hand, integrated tools, such as OpenStudio (Guglielmetti, et al., 2011) and DIVA-for-Rhino (Lagios, et al., 2010) have been developing to solve the problems with discrete processes. Currently integrated tools reside in a developmental process and their shortcomings in modeling, simulation and application is being resolved in each updated version.

Fundamental benefits of an integrated process rather than a discrete process are reducing errors and execution time. Modeling plays a key role in conducting an accurate simulation. In discrete processes, using two separate simulation tools increases the risk of errors created by discrepancies between the daylighting model and the energy model. In addition to the model, other shared information such as electric lighting controls and schedules of operation would be inserted once in an integrated process; therefore, fewer errors are generated because of dissimilarities between inputs in two separate simulation tools. Furthermore, transferring data from one simulation program to the other would require more time and management.

Koti and Addison (2007), An and Mason (2010) incorporated Daysim, a RADIANCE-based lighting simulation tool, into DOE-2, a whole-building simulation tool. Both studies aimed to show a difference in building energy savings when benefits of daylighting were more accurately calculated in
the simulation process. As the results show, Daysim provided more accurate results for daylight availability in the models. The reason lies in the fact that Daysim uses backward raytracing algorithm rather than split-flux algorithm generic to DOE-2.2. In addition, Daysim uses the Daylight Coefficient method for climate-based daylighting simulation whereas, DOE-2 uses interpolated design day method explained in lighting simulation types.

Koti and Addison investigated various daylighting configurations such as sidelighting, simple skylights and roof monitors via simulation of a classroom in Berkeley, CA. In their study, they used DOE-2.1E since it was the last version of DOE-2 that allowed scripting functions to read data from external files (Koti and Addison, 2007). The classrooms were modeled with a simple cubical geometry.

The effect that daylighting has on heating and cooling energy use was not accurately reported in this study. Researchers stated that increase/decrease in heating and cooling energy use was leveled by the corresponding increase/decrease of artificial lighting reduction (Koti and Addison, 2007).

An and Mason calculated energy consumption in an office building in Syracuse, NY, by the use of Daysim for daylighting through Ecotect and DOE-2.2 for energy simulation through eQuest. This study was successful to show an increase in building energy savings when daylighting was more accurately calculated with Daysim. The authors concede that the Daysim method resulted in an additional 32% (0.4 kWh/sqft/year) and 21% (0.1 kWh/sqft/year) reduction in two separate building spaces facing east and west respectively. This paper also investigates the effects that using Daysim has on heating and cooling energy simulation results from DOE-2.2.

Although the results discuss heating and cooling energy consumption in buildings, the type of HVAC systems, COP of systems, schedules of operation and the electric energy used by fan were ignored. The two simulated spaces did not have a simple geometry that could be used for a general application to a larger number of buildings. Furthermore, little information is provided about geometric and material properties of the two spaces. In addition, rather than hour-by-hour Daysim schedules, An and Mason used a simplified average daily lighting control schedule for each moth in simulation process.

There are limitations in both studies. Neither of the studies focused on design and optimization of daylighting systems. Radiance parameters, which are crucial in ensuring accuracy in backward raytracing daylighting simulation, were not controlled nor reported by the simulators. In addition, both studies were limited to one climatic condition.
Openstudio and DIVA 2.0 are two simulation programs that integrate daylight and thermal analysis by integrating RADIANCE/Daysim and EnergyPlus. In both Openstudio and Diva, energy simulation is conducted by EnergyPlus engine. For daylight analysis, both Openstudio and DIVA use RADIANCE for one-timestep daylight calculations, and Daylight Coefficient Method (used in DAYSIM) for annual daylighting simulation (Guglielmetti et. al., 2011, Lagios, et. al., 2010). For annual daylight availability, OpenStudio has recently added a 3-phase DC approach to its list of climate-based simulation types (Guglielmetti and Scheib, 2012). See table 3 for summary of comparison between DIVA and OpenStudio.

Table 3 Comparison of Openstudio and Diva, two integrated simulation tools for daylighting and energy analysis

<table>
<thead>
<tr>
<th>Simulation Tools</th>
<th>OpenStudio</th>
<th>DIVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daylight Analysis</td>
<td>Radiance</td>
<td>Radiance</td>
</tr>
<tr>
<td>Single point-in-time</td>
<td>Daylight Coefficient Method</td>
<td>Daysim</td>
</tr>
<tr>
<td>Annual</td>
<td>(Daysim)</td>
<td></td>
</tr>
<tr>
<td>Energy Analysis</td>
<td>EnergyPlus</td>
<td>EnergyPlus</td>
</tr>
</tbody>
</table>

**Openstudio**

Openstudio is the U.S. Department of Energy’s middleware software development kit. It creates a plug-in to SketchUp that develops series of scripts to support Radiance analysis and EnergyPlus simulation.

In Openstudio, the model is created in Google SketchUp environment. The model is drawn with heat transfer surfaces that accept thermal properties such as surface types, construction materials, and outside boundary conditions. A single model is drawn for both daylighting and energy simulation. The model information is saved in the .osm format and shared by both daylighting and thermal simulations. This file contains geometry, basic material properties, site, and weather file information. When exterior surfaces of a model are created, other interior surfaces such as thicknesses of walls and light-wells of skylights could be drawn with interior partition group.

To convert .osm file to a valid Radiance mode, Ruby is used for scripting. Ruby is an open source scripting language used to translate SketchUp geometry to be readable in Radiance. DaylightSim.rb is
a script in Ruby language, which enables the user to perform a variety of simulations with Radiance tools. These simulations could generate daylight coefficient (DC), discrete time step simulation (dcts), old Radiance single-sky single-time illuminance (ts), and glare analysis from fish-eye views from a point defined in the space (glare).

Openstudio is capable of creating more than one thermal zone. Once the thermal zones are defined and assigned to the spaces, adiabatic interior surfaces shared between the spaces are identified.

One factor to integrate Openstudio to EnergyPlus is to make thermal zones and material properties readable for EnergyPlus. “Model Editor” in OpenStudio is responsible for that task and it generates or modifies imported idf files, which is the format used in EnergyPlus. Model Editor is an interface needed in Openstudio, since the detailed idf files are not accessible through SketchUp plugin. The Model Editor allows modifying information about zone load and material properties.

Zone Loads is mostly related to internal heating and cooling loads in a space including, number of people per zone floor area, occupancy schedules, light power density, lighting schedules, electric equipment schedule, and infiltration rate and infiltration schedule. Material Properties is related to the layers of materials and their thicknesses used in the building envelope.

Another step that Openstudio takes towards integration of Radiance and EnergyPlus simulation is to reconcile thermal zones and daylight zones in the modeling process. In EnergyPlus, models are generally divided into thermal zones but the boundaries of thermal zones do not necessarily align with architectural massing. In Openstudio, thermal zones are created, but for daylighting purposes, some of the boundaries of the thermal zones could be introduced as “air walls”. Air walls are the boundaries that exist in thermal simulation but disappear in daylight simulation to avoid obstruction of daylight flow in the model (Guglielmetti et. al., 2011).

**DIVA 2.0**

Simulations in DIVA are controlled from a toolbar integrated into the Rhinoceros interface. Two buttons, Thermal Materials and Energy Metrics, control EnergyPlus simulation parameters. Upon running any DAYSIM climate-based simulation from DIVA, Daylight Autonomy profiles, shading schedules and electric lighting schedules are automatically generated based on the kind of user shading behavior chosen and the annual illuminance profile generated by DAYSIM at the selected
workplane sensor nodes (Jakubiec and Reinhart, 2011). One limitation of Diva is that the thermal simulation only runs for a single-zone thermal model.

Once the model is made in Rhinoceros, it should go under a layer called “Radiance Geometry”, which is the daylighting model in Diva. Thermal model must be a simple model built as planes in a separate layer called “DIVA Thermal”; thermal model, in fact, is a simplified version of the complex building geometry used in the daylighting simulations (Jakubiec and Reinhart, 2011). The geometry on the DIVA Thermal layers will never be exported to DIVA-Daylighting simulations.

DIVA-Thermal layer includes these options for surfaces: adiabatic surfaces, ceiling, floor, shading surface, wall, window and clerestory window. Some parameters that could be modified in Diva are occupant density, equipment power density, and air change per hour. In regard to “conditioning systems”, parameters such as heating/cooling efficiency, cooling/heating set point/setback and natural ventilation could be introduced as inputs for simulation.

Electric lighting control systems could be chosen in Diva based on a variety of options including a manual on/off switch, occupancy controls (switch off by occupancy, switch on/off by occupancy), and photosensor controls (photosensor controlled dimming, switch off by occupancy with dimming, switch on/off by occupancy with dimming) (Jakubiec and Reinhart, 2011).

One specific potential of Diva over Openstudio is the “shading control” options. Diva 2.0 models “occupants’ behavior” and it controls changes of blinds status due to occupants’ responses to light levels on workplane. Manual on/off switches and manual blinds create more complex situations than automatic electric controls and automatic blinds, because their function depends on the occupants’ behavior, which differs significantly from one person to another.

To manage various lighting conditions of a space in daylighting simulation programs, Lightswitch-2002 was proposed and it is planned to be used in future versions of Diva. Lightswitch suggests an algorithm to determine the level of electric lights used in a virtual space based on occupancy and available illuminances while predicting users’ behavior (Reinhart, 2002). The Lightswitch-2002 model works based on scenarios of people behavior and assumptions such as the fact that all occupants act consciously in response to daylight and turn off lights when enough natural light is provided in a space.
2.2.2.3. Simulation Tools Specific to Roof-daylighting Systems

SkyCalc

In order to conduct accurate energy analysis in buildings, simulations based on hourly local weather data are required to estimate annual daylight availability and building energy use. Prior studies have had deficiencies as they either address the impact of only electric lighting energy savings on building energy use for limited rooflighting options or investigate total energy use for skylights in flat roofs (Yoon 2008, Heschong and McHugh 2000; Lauodi and Atif 1999).

SkyCalc was the first tool to predict energy savings of skylights in some building functions (HMG SkyCalc 2.0). SkyCalc is a simple daylight and building simulation spreadsheet that considers the following effects of skylights on energy consumption:

- Reduced electricity consumption by electric lighting
- Reduced internal heat gains by electric lighting
- Increased solar gains
- Increased thermal transmittance of roof (data generation in SkyCalc is explained Appendix 1).

However, some limitations in SkyCalc do not make it a comprehensive tool for predicting energy performance of rooflit buildings:

- SkyCalc is limited to regular diffuse skylights and it does not provide a modeling space for design of various toplit configurations such as monitors and sawtooth roofs. Effects of shading elements and light distributors cannot be evaluated via SkyCalc. Design parameters for skylights are predefined based on assumptions and default values that reduce applicability of the tool to all rooflighting cases.

- Using SkyCalc is complex for locations other than the state of California; the climate files available in SkyCalc are limited to 48 locations in California. In order to simplify the process of energy use calculation, SkyCalc comes with special weather files that contain specific information acquired from a simulated “reference” building in DOE-2 for each location in California. This information includes hourly interior illuminances, sensible heat gains, and solar heat gains. Therefore, SkyCalc does not perform with typical weather data.
• SkyCalc accounts for hourly heating and cooling loads based on the simulation of the “reference” building in DOE-2. However, it does not provide an accurate internal heat gain calculation because it does not account for factors such as number of occupants, activity, and clothing inside a room.

• Spacing between the skylights is not a flexible parameter in the tool and it is assumed to be equal between all apertures in all cases; in addition, SkyCalc does not optimize the spacing as a parameter to increase lighting uniformity and improve performance of the system.

THERM/WINDOW

WINDOW 6.3 and THERM 6.3 are software programs developed at Lawrence Berkeley National Laboratory (LBNL) to determine the thermal and solar optical properties of glazing and window systems (LBNL, 2008). WINDOW 6 provides an extensive library of glasses to choose from. In addition, glazing systems library, shading layer library, frame library, and window library (e.g. fixed, sliding, vertical, or horizontal) enables modeling variety of glazing systems and analysis of their optical and thermal performance. By choosing the desired glass material, frame, and type of window, the program calculates Visible transmittance (VT), solar heat gain coefficient (SHGC), and U-factor of the window. However, WINDOW does not allow drawing the window and customize the size or frame details of windows. To account for the effects of the detailed components of frame, THERM should be used along with the center-of-glazing results from the WINDOW program.

THERM is a module of the WINDOW 5 program for analyzing the two-dimensional heat transfer through buildings products such as windows, walls, foundations, roofs and other products whereby thermal bridges occur (LBNL, 1998). THERM 6.3 is the most current version in 2013 that performs two-dimensional conduction heat-transfer analysis based on finite-element method, which enables modeling of complicated geometries of building components. THERM allows drawing or inserting cross sections of building products for analysis. When material properties, and boundary conditions are defined the model is ready for analysis. Results of analysis include U-factor, isotherms, heat-flux vectors, and local temperatures.

Algorithms in WINDOW/THERM

In WINDOW/THERM programs, the total fenestration product properties for U-factor, SHGC and VT are based on an area-weighted average of the product's components:

• The center-of-glazing properties of the glazing system
The frame edge and divider edge properties depend on the center-of-glazing properties of the associated glazing system (THERM Manual LBNL, 2006). The process of calculation includes the following steps:

1. Multiply the component property by the component area
2. Sum these area-weighted component properties
3. Divide the area-weighted sum by the total projected area of the product

The operator types (fixed, vertical slider, horizontal slider, casement) determine which components (head, jamb, sill and meeting rail) are required to calculate the whole product area-weighted values.

**U-factor:** the whole-product area weighted U-factor calculation is based on the following formula:

\[
U = \frac{\sum(U \cdot A) + \sum(U \cdot A) + \sum(U \cdot A) + \sum(U \cdot A)}{A_{pf}}
\]

Where:

\[U_i = \text{Total product U-factor, W/m}^2\text{-oK} \text{, (Btu/hr-ft}^2\text{-oF)}\]
\[A_{pf} = \text{Projected fenestration product area, m}^2\text{(ft}^2\text{).} \]
\[U_f = \text{Frame U-factor, W/m}^2\text{-oK} \text{, (Btu/hr-ft}^2\text{-oF).} \]
\[A_f = \text{Frame area, m}^2\text{(ft}^2\text{).} \]
\[U_d = \text{Divider U-factor, W/m}^2\text{-oK} \text{, (Btu/hr-ft}^2\text{-oF).} \]
\[A_d = \text{Divider area, m}^2\text{(ft}^2\text{).} \]
\[U_e = \text{Edge-of-glazing U-factor, W/m}^2\text{-oK} \text{, (Btu/hr-ft}^2\text{-oF).} \]
\[A_e = \text{Edge-of-glazing area, m}^2\text{(ft}^2\text{).} \]
\[U_de = \text{Edge-of-divider U-factor, W/m}^2\text{-oK} \text{, (Btu/hr-ft}^2\text{-oF).} \]
\[A_de = \text{Edge-of-divider Area, m}^2\text{(ft}^2\text{).} \]
\[U_c = \text{Center-of-glazing U-factor, W/m}^2\text{-oK} \text{, (Btu/hr-ft}^2\text{-oF).} \]
\[A_c = \text{Center-of-glazing area in ft}^2\text{(m}^2\text{).} \]

Solar Heat Gain Coefficient (SHGC): the total solar heat gain coefficient is determined by an area-weighted average of contributions from the transparent and the opaque elements in the fenestration product. The SHGC is a function of the solar transmittance, the solar absorptances of each layer and the inward flowing fraction of thermal energy. The SHGC is calculated for each component of the product separately. All the transparent regions (center-of-glazing, edge-of-glazing, and edge-of-
divider) have the same SHGC. Once the SHGC of the opaque elements is determined the total SHGC is calculated as the area-weighted average of the SGHC through the transparent and the opaque portions of the fenestration product as shown below.

\[
\text{SHGC}_t = \left[ (\text{SHGC}_f \times A_f) + (\text{SHGC}_d \times A_d) + (\text{SHGC}_e \times A_e) + (\text{SHGC}_{de} \times A_{de}) + (\text{SHGC}_c \times A_c) \right] / A_{pf}
\]

Where:

- \(\text{SHGC}_t\) = Total product SHGC (dimensionless).
- \(A_{pf}\) = Projected fenestration product area, \(\text{m}^2\) (ft\(^2\)).
- \(\text{SHGC}_f\) = Frame SHGC (dimensionless).
- \(A_f\) = Frame area in, \(\text{m}^2\) (ft\(^2\)).
- \(\text{SHGC}_d\) = Divider SHGC (dimensionless).
- \(A_d\) = Divider area in, \(\text{m}^2\) (ft\(^2\)).
- \(\text{SHGC}_e\) = Edge-of-glazing SHGC (dimensionless).
- \(A_e\) = Edge-of-glazing area in, \(\text{m}^2\) (ft\(^2\)).
- \(\text{SHGC}_{de}\) = Edge-of-divider SHGC (dimensionless).
- \(A_{de}\) = Edge-of-divider Area in, \(\text{m}^2\) (ft\(^2\)).
- \(\text{SHGC}_c\) = Center-of-glazing SHGC (dimensionless).
- \(A_c\) = Center-of-glazing area, \(\text{m}^2\) (ft\(^2\)).

Visible Transmittance: the whole-product area weighted visible transmittance calculation is shown below.

\[
\text{VT}_t = \left[ (\text{VT}_f \times A_f) (\text{VT}_d \times A_d) + (\text{VT}_e \times A_e) + (\text{VT}_{de} \times A_{de}) + (\text{VT}_c \times A_c) \right] / A_{pf}
\]

Where:

- \(\text{VT}_t\) = Total product VT (dimensionless)
- \(A_{pf}\) = Projected fenestration product area, \(\text{m}^2\) (ft\(^2\)).
- \(\text{VT}_f\) = Frame VT (dimensionless).
- \(A_f\) = Frame area, \(\text{m}^2\) (ft\(^2\)).
- \(\text{VT}_d\) = Divider VT (dimensionless).
- \(A_d\) = Divider area, \(\text{m}^2\) (ft\(^2\)).
- \(\text{VT}_e\) = Edge-of-glazing VT (dimensionless).
- \(A_e\) = Edge-of-glazing area, \(\text{m}^2\) (ft\(^2\)).
- \(\text{VT}_{de}\) = Edge-of-divider VT (dimensionless).
- \(A_{de}\) = Edge-of-divider, \(\text{m}^2\) (ft\(^2\)).
- \(\text{VT}_c\) = Center-of-glazing VT (dimensionless).
- \(A_c\) = Center-of-glazing area, \(\text{m}^2\) (ft\(^2\)).
2.2.3. Thermal Comfort Models

Mathematical models have been developed to predict human comfort in built environment. Thermal comfort models are similar in terms of applying an energy balance to a person. These models use the energy exchange mechanisms in addition to physiological parameters resulted from experiments to predict thermal sensation. The models differ in representation of heat transfer from and through the body and the human control system. They are also divergent in defining criteria for the state of thermal comfort (US DOE 2010). In this chapter, most notable models of thermal comfort will be illustrated.

2.2.3.1. Fanger Comfort Model

Fanger’s Comfort model was the first developed model for thermal comfort (Fanger 1967, 1970). This model considers human body as a whole and assumes no thermoregulatory effects; a steady state is assumed at thermally neutral condition for the body (Rizki et al. 2011). Fanger's model takes into account all the modes of energy loss from the body including convection and radiant heat loss. The model calculated energy loss by determining the skin temperature and evaporative sweat rate for a thermally comfortable person in a given set of conditions.

\[ Q_{\text{dry}} = Q_c + Q_r \]
\[ Q_c = h_c \times f_{cl} (T_{cl} - T_a) \]
\[ Q_r = f_{eff} f_{cl} \varepsilon \theta (T_{cla}^4 - T_{rad}^4) \]

Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are two indices proposed in Fanger’s model that the international Standard ISO 7730 uses to predict the occupants’ thermal sensation and specify acceptable thermal condition for an environment (ISO, 2005).

2.2.3.2. Two-Node Model

Two research institutes developed the two-Node Model known as Pierce two-node model and KSU two-node model. The two-node model takes physiological responses to transient situations into account (Gagge et.al. 1986). This model considers human body as two isothermal, concentric compartments, one representing the internal section or core, the other representing the skin. This fact accounts for the passive heat conduction from the core to the skin (Gagge et.al. 1986).
The Pierce two-node model was developed at the John B. Pierce Foundation at Yale University and expanded until the most recent version in 1986 ASHRAE Transactions (Gagge et.al. 1970, 1986). The latest version (Fountain and Huizenga 1997) suggests that an actual environment is converted to a standard environment with SET and ET. The SET or Standard Effective Temperature is the dry-bulb temperature of an environment with 50% relative humidity and standard clothing. ET or Effective Temperature is the dry-bulb temperature of an environment with uniform temperature ($T_{air}$ = Mean Radiant Temperature) where the subjects would experience the effects of a real environment. The latest version of the model suggests that the classical Fanged PMV be modified by using ET or SET instead of the operative temperature.

\[
PMV_{ET} = (0.303 e^{-0.036M} +0.028) (H - L_{ET})
\]

\[
PMV_{SET} = (0.303 e^{-0.036M} +0.028) (H - L_{SET})
\]

PMV: predicted Mean Vote modified by ET or SET

$L_{ET}, L_{SET}$: All the modes of energy loss from body at ET, or SET

$H$: Internal heat production rate of an occupant per unit area (= $M - W$)

$M$: Metabolic rate per unit area

The KSU two-node model was developed at Kansas State University (Azer and Hsu 1977), which is similar to the Pierce model. The main difference between the two models is that the KSU model takes into account the difference in thermal sensations in cold and warm environments. The Thermal Sensation Vote (TSV) is calculated with a different formula in the KSU model and it differs in cold and warm environments.

2.2.3.3. Adaptive Comfort Models (ASHRAE 55)

This method accounts for personal adjustments to surroundings to reduce physiological strain in forms of conscious action (e.g. activity level, clothing, and ventilation) or unconscious action (e.g. sweating, shivering) (ASHRAE 55-2010, Rizki et al. 2011). The adaptive model defines two comfort zones based on different levels of acceptability: 80% and 90% acceptability (US DOE 2010).

Adaptive comfort model based on European standard EN15251-2007 is similar to ASHRAE 55-2010, but different in curves of the indoor operative temperature and acceptability limits. This model is intended for use in naturally ventilated buildings (US DOE 2010).
2.2.3.4. Graphic Comfort Zone Method

In ASHRAE 55-2010, Graphic Comfort Zone Method is defined as one of the three compliance paths to meet the requirements in this standard. Graphic Comfort Zone is a simplified method based on the widely used thermal comfort chart (figure X). It includes a “comfort zone” which is improved and enlarged in 2010 standard. It should be highlighted that the graphic cannot be applied based on dry-bulb temperature; in fact, the graph represents operative temperature, which is typically defined as 0.5 dry bulb air temperature plus 0.5 mean radiant temperature for still air.

Figure 6 Graphic Comfort Zone Method in ASHRAE 55-2010
The upper limit for humidity in Graphic Comfort Zone Method is 0.012 humidity ratio, which is a strict limit. This limit gives a flat top for the comfort zone. In “summers”, comfort zone shifts to the right based on lightweight clothing (0.5 clo) and limits to 67% and 56% relative humidity at the flat top of comfort zone. In “winters”, with heavyweight clothing the comfort zone moves towards left.

2.3. Comparison and Conclusion

Comparing various tools for lighting and energy simulation tools, integrated whole-building energy simulation methods that enable both lighting and energy simulation via a single program rather than two separate tools are more advantages. This section first focuses on the benefits and limitations of two integrated whole-building energy simulations: DIVA-for-Rhino and OpenStudio.

One advantage of Openstudio over Diva 2.0 is that Openstudio is capable of creating more than one thermal zone, where as, Diva 2.0 handles only one thermal zone. For the current Ph.D. research, only one thermal zone is required for modeling skylights and roof monitors. More explanation about thermal models will be provided in chapter 4.2.

Another advantage of Openstudio over Diva 2.0 is to have “Model Editor” as a separate application responsible for modification of idf files. Model Editor allows an easy access to EnergyPlus files and it provides a comprehensive menu of design parameters that influence thermal performance in a space. However, in Diva 2.0, direct access to idf files is not provided and some limited design parameters are accessible directly with the DIVA graphic use interface (GUI). In addition, importing construction materials with different thermal properties is simpler in Openstudio via Model Editor.

However, Openstudio has currently several limitations. Creating building model in SketchUp for OpenStudio is not as quick and straightforward as modeling in Rhino for DIVA. Adding details to models require extra steps in OpenStudio. As an instance, thickness of walls and light-wells of skylights should be drawn with “interior partition group” application. The first important limitation of OpenStudio is that all Radiance materials are not yet supported. Radiance materials “plastic” and “glass” are supported but support for “trans” and the new “BTDF” materials are planned for future development of the software. Translucent materials, which are mostly used for roof-daylighting systems are not supported and complete support for BTDF is under development. Currently all Radiance functionality is accessed via the command line interface (CLI) and Radiance parameters and materials could not be defined with the OpenStudio graphic use interface (GUI).
Despite significant improvements, the existing integrated whole-building energy simulation tools need further development. They must advance capabilities in lighting and energy simulations via user-friendly interface. Improving data sharing and data exchange from one simulation engine to the other is crucial in advancement of these tools. In order to have correct interpretation of results achieved from such integrated simulation tools, users have complete knowledge about the inputs and the default values used by the program for simplification purposes.

SkyCalc is an inspiring tool and its objectives are followed in the current study. However, its limitations in accepting a wide range of weather data files, changing model parameters, and using an accurate daylighting simulation algorithm will be resolved by the proposed method in this study. More information will be provided in chapter 4 that focuses on the research methodology.

WINDOW/THERM are useful programs to identify lighting and thermal properties of materials in simulation inputs. Due to limitations of WINDOW in changing the size of window, the algorithms will be used for calculation of thermal properties of the materials (calculation of U-value). Next chapter will outline the conceptual framework of this study.
CHAPTER 3:

CONCEPTUAL FRAMEWORK AND RESEARCH QUESTION

2.1. CONCEPTUAL FRAMEWORK

This research tries to evaluate visual and thermal performance of daylighting systems that admit daylight inside buildings through roofs. Figures X and Y show the conceptual framework for this study, while the solid blue lines on the boundary of boxes highlight the main concepts of this study. This research targets horizontal buildings where the building roof expands over a large surface area with a large ratio to area of vertical surfaces. Main focus of the research is office buildings with 8’-10’ ceiling height, which are considered low ceiling spaces in comparison with retail stores and warehouses.

Figure 1 Research framework in terms of roof daylighting systems types and performance
The types of roof-daylighting systems to be investigated in this research include:

1. Horizontal apertures in flat roofs known as skylights with linear and square forms.
2. Vertical apertures facing in two opposite directions known as roof monitors, orientated in north-south or east-west direction.

In evaluation of performance of roof-daylighting systems, only physiological needs of occupants will be discussed. Evaluation based on psychological, sociological, and economic needs of people require exhaustive time and budget which goes beyond the limitations of the current study.

In this research, performance evaluation of roof-daylighting systems is based on definition of a well-designed daylit room. A daylit room is defined as “a space that is primarily lit with natural light and that combines a high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling (Reinhart, 2010)”. Although daylighting has been a topic of investigation for over thirty years, consensus is not reached for a metric that truly represents daylighting quantity and quality. Sufficient illuminance at various points of a space is required to ensure enough daylight for occupants to perform a visual task. This study focuses this basic but fundamental requirement, and measures illuminance in spaces at various times of year under different sky conditions. In order to ensure a visually comfortable space without discomfort glare, this study focuses on glare probabilities in spaces with roof daylighting systems. Daylight Glare Probability (DGP) is used as a metric to identify and estimate glare problem in such spaces and suggest design solutions to resolve the problem.

Energy efficiency is the most important goal that this study seeks through the design of roof-daylighting systems. The literature review revealed that skylights and other toplighting systems are not extensively applied in buildings due to their initial costs and additional operations costs. This study tries to collect precise energy performance data on properly designed roof-daylit buildings and investigate possibility of energy saving in those buildings. Energy use intensity (EUI) and annual building operation costs are two metrics used for indication of energy consumption in each design. Judgment about energy-efficiency is made based on comparison of each case with a base case, which is designed with no roof apertures.

In addition, providing thermal comfort is a crucial concern that is targeted along with other design goals. Regarding the effects that daylighting has on thermal sensation of people in an enclosed space, special care is dedicated to the design of HVAC system. The literature review revealed that the thermostat control in conventional HVAC systems is based on mean air temperature measured by a
sensor placed in the return air path. However, this method ignores the radiant temperature felt by occupants inside a room with windows. Therefore, the thermostat is controlled by operative temperature, a combination of mean air temperature and mean radiant temperature. The graphic comfort zone method is used to ensure thermal comfort in all occupied hours of the buildings as it is recommended in ASHRAE 55-2010.

This study uses computer simulation method including both lighting and energy simulations in design models. DIVA-for-Rhino, which is an integrated simulation tool was chosen because it combines Radiance and EnergyPlus simulation tools. Based on the literature review, Radiance was chosen because it provides an accurate lighting simulation tool with backward ray tracing algorithm and it is extensively validated. Both single-point-in-time and climate-based daylighting simulations are conducted in this study. Climate-based daylighting is provided by DAYSIM, which utilizes DC daylight coefficient method, in DIVA-for-Rhino package. Energy simulations are performed with EnergyPlus, which is validated and widely used for building performance analysis as explained in chapter 2.
Advantage of Diva to OpenStudio for the current study is that DIVA provides more advanced options for lighting simulation rather than OpenStudio.

1. There is not a graphic interface for changing Radiance Parameters in daylighting analysis in OpenStudio
2. It is not possible to draw the geometry with light-wells in three-dimensional models. In fact, separation of Daylight and Thermal models in DIVA has the benefit of including more details that have influence on the illuminance received at task surface in daylighting simulation.
3. OpenStudio does not support various Radiance parameters with GUI (Graphic User Interface) yet. Therefore, customizing Radiance materials (e.g. creating translucent materials) and changing Radiance simulation parameters are not convenient through the use of OpenStudio plug-in.

For energy simulation, DIVA is coupled with EnergyPlus in this study. The reason lies in the fact that DIVA has not yet provided an extensive list of options for construction material, Operation schedules, and HVAC system design. Therefore, to customize these options, idf scripts generated from DIVA were inserted and modified in EnergyPlus.

### 2.2. RESEARCH OBJECTIVES AND RESEARCH QUESTIONS

Goals of this study the following items:

- Define a range of common or promising rooflighting configurations, including construction details, structural sizing, and selective construction cost assessments, for a range of climates.
- Simulate and evaluate the daylighting effectiveness for special configurations of rooflighting systems.
- Simulate and evaluate the thermal performance of the special configurations of rooflighting systems.
- Estimate savings in energy consumption and building operation costs through application of the suggested roof daylighting systems.
- Design optimization of roof daylighting systems based on energy consumption and building operation costs.
- Make recommendations regarding applicability of the systems to various building types and climates.
This study will clearly ground the research analyses in architectural reality, with all the assumptions regarding the daylight glazing, thermal envelope, building structure, thermal conditioning system, and electric lighting type, layout, and controls clearly identified in the context of the overall building design.

This paper will provide:

- Information about performance of horizontal and vertical roof apertures in two different locations with distinct climatic conditions
- A comprehensive assessment of the energy performance of properly designed horizontal apertures, including thermal effects
- Design optimization for skylights and roof monitors.

Research Questions are the followings:

- How can each roof daylighting system be optimized to reach the best results in terms of daylighting without creating visual discomfort?
- How much is the daylight illuminance received on the workplane in a room with square and linear horizontal apertures (skylights) in a flat roof?
- How much is the daylight illuminance received on the workplane in a room with vertical apertures facing in two opposite directions (roof monitors) facing north-south and east-west directions?
- How does daylight illuminance change on task level by changing the section design of horizontal apertures (skylights) in flat roofs?
- How does daylight illuminance change on task level by changing the size of horizontal apertures (skylights) in flat roofs?
- How does daylight illuminance change on task level by changing the section design of roof monitors facing north-south?
- How does daylight illuminance change on task level by changing the size of roof monitors facing north-south?
- How much glare is created in the space as a result of skylights in flat roofs?
- How much glare is created in the space as a result of roof monitors facing north-south?
- How can each roof daylighting system be optimized to reach the best results in terms of energy consumption?
- How much energy consumption is changed when the size of skylights in flat roofs change?
• How much energy consumption is changed when the size of roof monitors facing north-south change?

• How much energy consumption is changed when the orientation of vertical roof apertures change from facing north-south to facing east-west direction?

3. What are the potential savings in building operating energy and operating cost that can be achieved by implementing different designs for roof daylighting systems?

• How much is the building operation costs for skylights in flat roofs?

• How much is the building operation costs for roof monitors facing two opposite directions?

• Which configuration creates the most savings in building operation costs?

Although daylight can be admitted through any aperture in building, achieving the most efficient and effective interior illumination with sunlight requires care in the placement and design of the illumination glazing.

To achieve the maximum potential energy savings without reducing illumination effectiveness, the following requirements must be satisfied:

• The illumination aperture should be oriented to collect daylight effectively throughout the diurnal and seasonal cycles. More specifically, an attempt should be made to maximize the solar intensity on the illumination glazing, in order to minimize the required area of glazing, thereby minimizing both the capital cost of the glazing and deleterious thermal effects of conductive gains and losses through the building envelope.

• The collection of sunlight during the winter should be comparable to, or exceed, the collection during the summer, so that excess solar gains tend to occur more often during the heating season than during the cooling season.

• The collection of sunlight during a summer day should be as uniform as possible in order to meet the building illumination requirements without aggravation the cooling loads.

• The sunlight admitted through the apertures must be delivered to the task surface of the office building, this means delivering as much of the admitted sunlight as possible, as uniformly as possible, to the plane of the desk top.

• The room must be free of any glare, which would diminish the effectiveness of the illumination system.

Skylights are the most widely use configuration of roof daylighting. Skylights have the disadvantage that they face up towards the midday summer sun. When they are sized large enough to provide
adequate light quantity from diffuse skylight, then beam sunlight causes a thermal overload of approximately a factor of ten. When they are sized smaller, to avoid thermal overload, then they are only providing enough illumination when beam sunlight is available. Since beam sunlight is only available during about half the daylight hours in most locations, a substantial amount of energy is lost during times when beam sunlight is not available.

Furthermore, the illumination and energy benefits of skylights are also less than they could be because of the context in which they are typically used. For instance, the layering scheme of flat-roof construction reduces the daylighting performance, as illustrated in the results of this study.

The other limitations that should be considered at design stage are the followings:
1. Vertical surfaces of the room tend to be poorly illuminated unless openings are planned to cast light onto them
2. The ceiling is only illuminated by reflected light, so brightness contrast between the visible sky and the surrounding ceiling area can be excessive
3. There are usually unwanted specular reflections of the sky in horizontal work surfaces

The following steps should be taken at design stage:
4. Strive to make the illumination close to uniform by spacing the roof monitors fairly close together.
5. Strive to avoid thermal envelope degradation (curb and glazing edge effects) by not perforating the envelope any more than necessary.
6. Using diffusing material in roof apertures, thereby making the illumination on the work plane more nearly uniform.
7. Using light-colored interior surfaces, thereby increasing the amount of light reaching the work plane and increasing the amount of light reflected in the space, so that contrasts between the light sources and opaque surfaces are reduced.
8. Locate some of the roof monitors to make sure they wash walls with light.

In the next chapter, design parameters of roof daylighting systems will be explained, baseline settings for simulations will be outlined and the research process will be discussed.
CHAPTER 4: METHODOLOGY

4.1. RESEARCH DESIGN

This section discusses the independent variables, dependent variables, and building parameters of the study.

4.1.1. Independent Variables

1- Toplighting configurations and design
   • Skylights in flat roofs with square and linear apertures
   • Roof monitors with vertical apertures facing in two opposite directions.

2- Buildings location
   • Boston
   • Miami

3- The Glazing area to Floor area Ratio
   • For horizontal apertures: 2%, 3.5%, and 5%
   • For vertical apertures: 15%, 20%, 25%

4- Orientation (for vertical glazing)
   • North-South Axis
   • East-West Axis

5- Structural Notions
   For horizontal glazing:
   • Integrated Duct Systems and Structure
   • Un-integrated Duct Systems and Structure

   For vertical glazing:
   • 30 ft. expansion, with 24 in.-deep light well
   • 60 ft. expansion, with 36 in.-deep light well

6- Light-well configuration
   • Beveled/ sloped light wells
   • Squared off light wells
In this study skylights (horizontal apertures) in flat roofs and roof monitors are explored in Boston and Miami. These two locations were selected because they represent two substantially different climates in terms of daylight availability and thermal conditions in the United States. Glazing to floor area ratio for horizontal apertures varies from 2%, to 3.5% and 5% with a glazing material which has 42% visible light transmissivity (Tv). Glazing to floor area ratio for vertical apertures (monitors) varies from 15% to 20%, and 25% with a diffuse glazing material in south facing glass, which has 57% visible light transmissivity and a clear glass in north facing window, which has 72% visible transmissivity. Models are oriented in north-south axis; in addition, some simulations were run with roof monitors oriented to face east and west. Structural notions and light-well configurations are extensively explained the section on building parameters. Electric lighting control is a dimming control system and the vertical dimension from the finished floor to the top of the curbing supporting the daylight glazing in the roof is 13’ 7” in all the cases.

4.1.2. Dependent Variables

Performance evaluation of roof daylighting systems is categorized into three main sections based on the design goals discussed in chapter 3. These sections are daylight assessment, and whole-building energy assessment, and total operating energy cost assessment.

4.1.2.1. Lighting Assessment

Daylight assessment ensures sufficient illuminance throughout spaces in different sky conditions during all occupied hours of the buildings. Quantity and variability of illuminance on horizontal task surface are measured for daylight assessment.

*Single-time spatial distribution of daylight:* at this stage quantity of available daylight in toplit spaces are measured for a single moment. Simulation outputs will be summarized in terms of illuminance levels. Average illuminance on the work plane at a single moment in time is reported for each model. The metric used for evaluation of daylight variations in a space on work plane is the ratio of maximum to minimum illuminance in the space.

*Climate-based daylighting:* the annual daylight available in toplit spaces are measured based on the weather data of the special location.

*Electric Lighting:* electric lights required to substitute daylight deficiency to reach the illuminance target are calculated at this stage. The electric light is reported in units of kWh.
Glare and Visual Discomfort: Avoiding glare is important in spaces designed with daylighting. It is possible for sunlight to increase the electric lighting illumination levels required to achieve a satisfactory luminous environment. Such an effect is likely to be created in any situation where beam sunlight is allowed to slash through the work plane, thereby creating extreme contrast in the immediate filed of view of the person engaged in the primary work task. A common response to this kind of glare is to close drapes that are available or turn up the lights in order to even out illumination and reduce the contrast. In fact, with beam sunlight on the work plane, the level of electric lighting necessary to reduce the contrast to acceptable levels may be much higher than the level required to produce acceptable illumination intensity in a situation where the light contrast does not exist. In this research glare is estimated with Daylight Glare Probability (DGP) metric, explained in chapter 2.1.4.

Daylighting Performance Metrics.

4.1.2.2. Whole-building Energy Assessment

In whole-building energy assessment, total energy use in the daylit buildings over a year will be assessed and Energy Use Intensity (EUI) in toplit spaces will be reported. Different types of energy use, such as electricity and gas consumption for heating, cooling, equipment, fan, interior lights, and equipment are measured and building energy use intensity is reported in units of [kBtu/ ft²/ yr] for each roof-daylighting configuration.

4.1.2.3. Total Operation Energy Costs

Total energy costs of electricity and gas consumption in different roof-daylighting configurations is measured in this section. Results will be reported in Dollars per 900 ft² module and Dollars per square foot of floor area.

4.1.3. Building Parameters and Baseline Settings

The baseline parameters for the building in this study are:

- An office space of dimension 30-ft x 30-ft (9.14m x 9.14m) was modeled to represent a section cut from an infinite rooflit space. To avoid complicating the outputs with wall or partition effects, this space has been surrounded on all sides by eight other identical spaces in the daylighting model. Readers should remain cognizant of the fact that introducing partitions or walls will complicate the analysis and substantially alter the results.

- The height of roof, from finished floor to top of the curb, is 13’-7” (4.14 m) in all cases. Therefore, distance between the lower edges of the glazing to task-level remains constant in all cases.
• The baseline has an opaque roof with no apertures.

4.1.3.1. Horizontal Roof Apertures (Skylights)

In square skylights, the models have four square apertures located at the center of each quarter of the space (Figure 1) resulting in a uniformly spaced grid throughout the building. Vertical and horizontal dimensions of models are shown in Figure 1 and table 1. Building parameters that change in skylights include:

1. Depth and shape of the light-well through which the daylighting is entering:
   • The base case, having a squared-off light-well that is a vertical shaft with a vertical dimension of 5’-7” (1.70 m) and a flat ceiling everywhere between the light-wells (Figure 1A). The deep light-well shaft is a manifestation of the allocation of deep layers to each of the primary systems in typical roof construction. This deep roof leaves 8’ (2.4 m) clearance for the ceiling.
   • A system that has been refined for daylighting purposes (Figure 2B), in which:
      o The ceiling has been splayed outward around the lower edges of the light-well. For nomenclature clarity, we will say that the light-well is the vertical shaft. The sloped surface will be referred to as the sloped portion of the ceiling, having a vertical dimension of 2’-4” (0.71 m) and being set at a slope of 45°.
      o The structure and the ductwork have been integrated to reduce the vertical dimension of the light-well shaft to 1’-3” (0.38 m) (Figure 2B). In this configuration, the ceiling height has been increased to 10’ (3.04 m) because of the reduced depth of the roof.
   • A system that has been designed for maximum daylighting effects (Figure 2C), in which:
      o The ceiling has been splayed outward around the light-well in four directions with a sharp angle (60°) and extended until intersects with the other sloped light-wells. This design helps to minimize the flat surface created in between light-wells and it reduces the contrast between the brightest and darkest points of the ceiling resulting in higher lighting quality.
      o The space allocated for structure and ductwork is minimized to a space with rectangular cross section. As a result of this integrated design, the proportion of
interior space, which is occupied by ductwork is reduced resulting in a larger interior space.

- The ceiling height is 9’ at the lowest point underneath the triangular cross sections.

In linear skylights, two apertures are located at the center of each half of the roof in east-west axis. Linear apertures extend along the length of each module for 30’ and continue to the neighboring modules in east and west side.

All linear apertures are modeled with integrated ductwork into structure and beveled light-wells. Difference between squared-off linear apertures and integrated-beveled linear apertures in terms daylighting performance is discussed in a previous paper (Ghobad et. al. 2012).

![Figure 1: Floor plans in (A) square skylights (B) linear skylights](image)

**Table 1: Vertical dimensions of models**

<table>
<thead>
<tr>
<th>Skylights</th>
<th>Configuration</th>
<th>Ceiling Height</th>
<th>Constant Roof Height (Floor To Top Of The Curb)</th>
<th>Light-Well Depth</th>
<th>Curb Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-integrated Deep System</td>
<td>8’</td>
<td>13’ 7”</td>
<td>5’ 7”</td>
<td>6’ 1/2”</td>
<td></td>
</tr>
<tr>
<td>Integrated Shallow System</td>
<td>10’</td>
<td>13’ 7”</td>
<td>3’ 7”</td>
<td>6’ 1/2”</td>
<td></td>
</tr>
<tr>
<td>Extended Sloped Light-wells</td>
<td>Lowest point: 9’</td>
<td>13’ 7”</td>
<td>4’ 7”</td>
<td>6’ 1/2”</td>
<td></td>
</tr>
</tbody>
</table>
2. The glazing area, expressed as the Aperture to Floor area Ratio (AFR):
   - 2%
   - 3.5%
   - 5.5%
   - 7.5%
   - 10%
Figure 2(A) Un-integrated roof design with squared-off light-wells
Figure 2(B) Integrated roof design with splayed light-wells
Figure 2(C) Integrated roofs with extended splayed light-wells
Table 2 Key dimensions of models

<table>
<thead>
<tr>
<th>Units</th>
<th>Floor Area Illuminated</th>
<th>AFR</th>
<th>Number of Apertures</th>
<th>Clear Glazing Length</th>
<th>Clear Glazing Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft²</td>
<td>m²</td>
<td>%</td>
<td>ft</td>
<td>m</td>
</tr>
<tr>
<td>Square Apertures</td>
<td>900</td>
<td>83.6</td>
<td>2</td>
<td>2.08</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
<td>2.83</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.5</td>
<td>3.50</td>
<td>1.07</td>
</tr>
<tr>
<td>Linear Apertures</td>
<td>5.5</td>
<td></td>
<td>4</td>
<td>3.0</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td></td>
<td>2</td>
<td>3.0</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td>3.0</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The flat roof is composed of the following components in all skylight models:

1. Glazing material composed of two Lexan plastic sheets (LXSCGN9A5.GEC and LXSCGN8A6.GEC) which are translucent with 58.6% and 71.4% visible transmissivity resulting in an overall 42% visible transmissivity and solar heat gain coefficient of 0.317. The U-value of the double layer Lexan sheets are 0.46 Btu/hr-ft²·F (2.59 W/m²K), which meets the American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 90.1-2010 requirements. Dimension of glazing area in different models is depicted in table 2.

2. Curbs are 6 1/2” high and 2.5 in.-thick composed of 1.5 in.-thickwood and 1 in.-thick Styrofoam for insulation purposes. The total U-value of the assembly is calculated based on an area-weighted average of the components (table 3), which are: glazing, edge effects for the glazing, framing, and curbs. Table 4 shows the results.

The total U-value of the assembly is calculated based on an area-weighted average of the components, which are: (1) overall UA of the glazing assembly, and (2) UA for the curbs. Table 3 shows the results.

This procedure included the following steps that coincide with the algorithm used in WINDOW/THERM program described in chapter 2.2 (LBNL):

- Calculate the average U-value of glazing. The average U-value for the glass was calculated by area-weighted average of the three parts of the glass: center, intermediate section, and edges. Center of glazing, the double layer Lexan sheet, had U-value of 0.46 [Btu/hr-Ft²-K]/2.59 [W/m²K] with R=2.17. Edge of glazing was assumed to have R=1, U-value =0.98
An intermediate area was assumed to exist between the center of glazing and edges, which is a 2”-wide strip next to the edges. U-value of the intermediate area was assumed to be an interpolation of the U-values for center and edges of glazing. This value was calculated as R=1.47, U-value of 0.68 [Btu/hr-Ft2-K].

- Calculate the average U-value of curbs composed of 1.5 in.-thick wood and 1 in.-thick Styrofoam.
- Multiply the U-value of each component (glazing and curbs) by the component area (A) to calculate UA for each component.
- Sum these area-weighted component properties and calculate overall UA.
- Divide the area-weighted sum by the total projected area of the product and calculate average U-value for assembly, as referenced to the projected area, which is the footprint of the daylighting assembly. This puts the thermal information in a format suitable for input to EnergyPlus.

**Table 3 Effect of frames and curbs on overall U-values of the glazing**

<table>
<thead>
<tr>
<th>Aperture Type</th>
<th>AFR</th>
<th>Glazing Dimension</th>
<th>U Average of Glazing</th>
<th>Curb Height</th>
<th>Curb UA</th>
<th>Overall UA (Curb UA + Glass UA)</th>
<th>Average U-value for Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Glazing UA (W/m2K)</td>
<td>Btu/hr.Ft2 K</td>
<td>m</td>
<td>inch</td>
<td>Btu/hr. F</td>
<td>Btu/hr. F</td>
</tr>
<tr>
<td>Square Apertures</td>
<td>2</td>
<td>0.64 x 0.64</td>
<td>25&quot; x 25&quot;</td>
<td>3.41</td>
<td>0.60</td>
<td>2.61</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>0.86 x 0.86</td>
<td>34&quot; x 34&quot;</td>
<td>3.20</td>
<td>0.56</td>
<td>4.52</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>1.07 x 1.07</td>
<td>42&quot; x 42&quot;</td>
<td>3.09</td>
<td>0.54</td>
<td>6.66</td>
<td>0.17</td>
</tr>
<tr>
<td>Linear Apertures</td>
<td>5.5</td>
<td>2.29 x 0.25</td>
<td>90° x 9.9&quot;</td>
<td>3.74</td>
<td>0.66</td>
<td>4.07</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>2.29 x 0.34</td>
<td>90° x 13.5&quot;</td>
<td>3.47</td>
<td>0.61</td>
<td>5.15</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.29 x 0.46</td>
<td>90° x 18&quot;</td>
<td>3.28</td>
<td>0.58</td>
<td>6.50</td>
<td>0.17</td>
</tr>
</tbody>
</table>

3. The rest of the roof is covered with a layer of rigid insulation 7-inch (0.18 m) thick with U-value of 0.033 Btu/h.ft2 °F (R-30) or 0.187 W/m2 K to comply with ASHRAE Standard 90.1-2010 and regional building codes in the United States.

**Table 4 Properties of roof insulation layer**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Conductivity</th>
<th>Required Thickness to Codes</th>
<th>Required U-value by Building Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/(m*K)</td>
<td>(Btu.in.)/(ft2.hr.F)</td>
<td>Inch</td>
</tr>
<tr>
<td>Styrofoam</td>
<td>0.033</td>
<td>0.2288484</td>
<td>6.865452</td>
</tr>
</tbody>
</table>

70
4. A layer of 1.5-inch (0.04 m) corrugated steel decking.

5. A structural spanning layer extends over the entire footprint of the building, with 2-ft depth to accommodate the deepest spanning member.

6. An electric-lighting and hung-ceiling layer extends over the entire footprint of the building, with a depth of 4 inches (0.05 m).

4.1.3.2. Vertical Roof Apertures in Two Opposite Directions (Roof Monitors)

Roof monitors include:
(1) a single roof monitor, with linear, vertical apertures facing north and south, extending the length of the module and located at the middle of space. (figures 3A and 4).
(2) A double roof monitors, each with linear, vertical apertures facing north and south, extending the length of the module and located such the spacing of the modules is every 15 ft. and such that the centerline of one module is located 7.5 ft. from one side of the module and the centerline of the other module is located 7.5 ft. from the other side of the module. (figures 3B and 4).

The parameters for monitor roofing system are:

9. The insulated, opaque portions of the roof consist of 7-in. (0.18 m) thick Styrofoam with U-value of 0.033 Btu/h.ft².F (R-30) or 0.187 W/m²K to be in compliance with ASHRAE Standard 90.1-2010 and regional building codes in the United States.

10. The roof decking is supported by trusses in the vertical apertures and extending down into the opaque light well. (See Figures N through M for the monitor configurations.)

11. The height of roof, from finished floor to top of the curb under the glazing, is 13’-7” (4.14 m) in all cases. Therefore, the distance between the lower edge of the glazing to task-level remains constant in all cases.

12. The high portion of the roof (top of the monitor) is horizontal.

13. The low portion of the roof (between the monitors) slopes at 0.25 in. of fall per foot of horizontal run. Over 30 feet of horizontal run, this will be a drop of 7.5 in. For 60 feet of horizontal run, this will be a drop of 15.0 in. This slope is accommodated by a variable height curb beneath the glass. The curb depth at the high end is 4 in (table 6).

14. Curbs are 3.5 in. thickness, composed of 1.5in.-thick wood and 2 in.-thick Styrofoam for insulation purposes.
15. The sloping portion of the roof accommodates water runoff and provides a tapered plenum volume beneath it to conduct air for thermal conditioning and fresh air.

16. Longer runs of the roofing system will require deeper structure and a deeper plenum volume to conduct the required air for thermally conditioning the larger space. The deeper structure and plenum volume will require a deeper light well. For the purposes of this paper, two light-well depths were examined: 24 in. deep light well for the 30 ft. spans and 36 in. deep light wells for the 60 ft. spans (table 6).

17. All vertical and horizontal dimensions are shown in tables 5 and 6 and Figure 3.

18. The south-facing aperture is double-glazing composed of Velux Laminated glass with a diffusing interlayer and with Low-e coating and a layer of clear glass with Argon gas in the middle. This composite of layers result in a diffuse glazing material with visible transmissivity of 57%, which is appropriate to distribute the beam sunlight around the space and to reduce glare.

19. In the north-facing aperture is a double-glazing consisting of two layers of clear glass resulting in visible transmissivity (V_t) of 72%.

20. The actual visible light transmittance through all the daylight glazing is reduced by approximately 10% by the obstructing effect of the truss web members. As a result, the actual V_t of south facing and north facing apertures would be 51% and 65% respectively. Dimension of the glazing area in each model is shown in table 5.

21. The U-value of the center of the glass is 0.25 [Btu/hr-ft2-F] or 1.42 [W/m2-K] for both north and south facing glass.

22. The SHGC is 0.386 for south-facing and 0.312 for north-facing glass. Properties of glazing materials were acquired from the Lawrence Berkeley National Laboratory WINDOW 6.3 simulation tool.

23. The total U-value of the glazing assembly is calculated based on an area-weighted average of the components, which are: (1) glazing, and (2) curbs. Table 7 shows the results. This procedure included the following steps:

   o Calculate the average U-value of glazing. The average U-value for the glass was calculated by area-weighted average of the three parts of glass: center, intermediate section, and edges.

   o Center of glazing, for both north and south glazings, had U-value of 0.25 [Btu/hr-Ft2-K]/1.42 [w/m2K] with R=4. Edge of glazing was assumed to have R=1.3, U-value =0.75 [Btu/hr-Ft2-K]/4.26 [w/m2K]. An intermediate area was assumed to exist between the center of glazing and edges, which was assumed to be about a 2”-wide strip next to the edges. U-
value of the intermediate area was assumed to be an interpolation of the U-values for center and edges of glazing. This value was calculated as $R=2.0$, U-value of 0.50 [Btu/hr-Ft2-K]/2.84 [w/m2K].

- Calculate the average U-value of curbs composed of 1.5 in.-thick wood and 1 in. thick Styrofoam.
- Multiply the U-value of components (glazing and curbs) by the component area (A) and calculate UA for each component.
- Sum these area-weighted component properties and calculate the overall UA.
- Divide the overall UA of the assembly by the total projected area of the product and calculate average U-value for assembly. This gives an effective U-value for the hole in the insulated roof, which is in the form suitable for input to EnergyPlus.

24. The overhang for the south-facing glazing is designed to avoid some of the direct beam light. The projection of the south overhang is proportional to the glass height, producing a 12° angle of rejection between the surface of the glazing and the end point of the overhang. The north glazing has a minimal overhang of 2” projection, to accommodate detailing.

The parametric variations in the study of roof monitors are:

3. The depth of the light-well through which the daylighting is passing:

- The first case with 24 in. deep light well, with a floor to ceiling dimension of 11’ 6 ¾”
- The second case with 36 in. deep light well, with a floor to ceiling dimension of 10’ 6 ¾”
- The third case has been modified for increasing daylighting performance. Vertical light-wells have been significantly reduced in this case, by designing sloped light-wells that create a triangular cross section between each pair of apertures. This space with triangular cross section is allocated for placement of structural members and ductwork (figure 3C).

- The roof truss is sloped at a shallow angle (¼ in. of rise per foot of horizontal run) with a 7.5 in. vertical differential between the low end and the high end of the roof. The distance from the finished floor to top of the curb is 13’ 7” at low end of the 30’x30’ module.

- The third case with triangular cross section light-wells can accommodate structural and mechanical equipment required for structures that run for over 30’.
The curb height is a constant along the entire span of the structure, rather than the variable-height curb for other roof monitors. For this configuration, a curb depth of 8 in. was chosen. This provides enough depth at the low end to accommodate water accumulation in the water flow down the sloped lower surface. The depth of this curb near the bottom of the run does not have to be as great as was the case for the other configurations, where the flow along the lower parts of the roof is augmented by flow off the sides of the higher parts of the roof. In this configuration, the higher parts of the roof are sloped also, accommodating the flow of water along those higher portions of the building to the boundary of the building.

4. The glazing area, expressed as the Aperture-to-Floor-Area Ratio (AFR):
   - 15%
   - 20%
   - 25%

Summary of building dimensions in skylights and roof monitors is presented in table 8.
Figure 3(A) Two sectional views of Monitor-SingleNSglass-24"Lightwell-30'Span-20%SFR
Figure 3(B) Two sectional views of Monitor-SingleNSglass-36"Lightwell-60'Span-20%SFR
Figure 3(C) Two sectional views of Monitor-DoubleNSglass-24"Lightwell-30'Span-20%SFR
Figure 3(D) Two sectional views of Monitor-DoubleNSglass-36°Lightwell-60°Span-20%SFR
Figure 3(E) Two sectional views of Monitor-DarkNSglass-17 'Lightwell-30' Span-20%SFR
Table 5 Glazing dimensions in single and double roof monitors with various AFRs

<table>
<thead>
<tr>
<th>AF R</th>
<th>Length of Module</th>
<th>Reduction Factor On The Horizontal Glazing</th>
<th>Effective Horizontal Glazing Dimension</th>
<th>Glass Area In One Panel</th>
<th>Height Of The Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
<td>m</td>
<td>ft</td>
<td>m2</td>
<td>ft</td>
</tr>
<tr>
<td>Single Monitors (900 ft² /83.6 m²)</td>
<td>0.15 30 9.14 0.9</td>
<td>27 8.1</td>
<td>67.5 6.27</td>
<td>2.5 0.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.20 30 9.14 0.9</td>
<td>27 8.1</td>
<td>90 8.36</td>
<td>3.3 1.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25 30 9.14 0.9</td>
<td>27 8.1</td>
<td>112.5 10.45</td>
<td>4.2 1.28</td>
<td></td>
</tr>
<tr>
<td>Double Monitors (900 ft² /83.6 m²)</td>
<td>0.15 30 9.14 0.9</td>
<td>27 8.1</td>
<td>33.75 3.13</td>
<td>1.3 0.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.20 30 9.14 0.9</td>
<td>27 8.1</td>
<td>45 4.18</td>
<td>1.7 0.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25 30 9.14 0.9</td>
<td>27 8.1</td>
<td>56.25 5.23</td>
<td>2.1 0.64</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 Vertical dimension of roof components

<table>
<thead>
<tr>
<th>Roof Components</th>
<th>60’ Horizontal Run</th>
<th>30’ Horizontal Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decking</td>
<td>3”</td>
<td>3.0”</td>
</tr>
<tr>
<td>Insulation</td>
<td>7”</td>
<td>7”</td>
</tr>
<tr>
<td>Curb height at high end of sloped roof</td>
<td>4”</td>
<td>4”</td>
</tr>
<tr>
<td>Air Space at End</td>
<td>7”</td>
<td>4”</td>
</tr>
<tr>
<td>30ft drop</td>
<td>7.5”</td>
<td>7.5”</td>
</tr>
<tr>
<td>Another 30ft drop</td>
<td>7.5”</td>
<td>-</td>
</tr>
<tr>
<td>Light Well Depth</td>
<td>36”</td>
<td>24”</td>
</tr>
</tbody>
</table>
### Table 7 U-value of roof monitor assembles

<table>
<thead>
<tr>
<th>AFR</th>
<th>Glass Horizontal x Vertical Dimension</th>
<th>U Average of Glazing</th>
<th>Glazing UA</th>
<th>Curb Height (Curb is composed of)</th>
<th>Curb UA</th>
<th>Overall UA for Skylights (Curb)</th>
<th>Average U-value for Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m x m</td>
<td>ft x ft</td>
<td>W/m2K</td>
<td>Btu/hr.F12.K</td>
<td>Btu/hr.F</td>
<td>m</td>
<td>inch</td>
</tr>
<tr>
<td>Single Monitors (Length 30’/9.14m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2.25 x 0.76</td>
<td>7.5 x 2.5</td>
<td>1.86</td>
<td>0.33</td>
<td>6.13</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td>20</td>
<td>2.25 x 1.00</td>
<td>7.5 x 3.0</td>
<td>1.78</td>
<td>0.31</td>
<td>7.82</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td>25</td>
<td>2.25 x 1.28</td>
<td>7.5 x 4.2</td>
<td>1.73</td>
<td>0.30</td>
<td>9.50</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td>Double Monitors (Length 30’/9.14m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2.25 x 0.39</td>
<td>7.5 x 1.3</td>
<td>2.19</td>
<td>0.38</td>
<td>3.61</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td>20</td>
<td>2.25 x 0.52</td>
<td>7.5 x 1.7</td>
<td>2.02</td>
<td>0.36</td>
<td>4.45</td>
<td>0.25</td>
<td>9.75</td>
</tr>
<tr>
<td>25</td>
<td>2.25 x 0.64</td>
<td>7.5 x 2.1</td>
<td>1.92</td>
<td>0.34</td>
<td>5.29</td>
<td>0.25</td>
<td>9.75</td>
</tr>
</tbody>
</table>

### Table 8 Summary of vertical dimensions in models

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Horizontal Run</th>
<th>Monitor Width</th>
<th>Ceiling Height</th>
<th>Roof Height</th>
<th>Light-Well Depth</th>
<th>Curb Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitors with squared off light-wells</td>
<td>60 ft.</td>
<td>Single Monitor 30ft Wide</td>
<td>10' 6 3/4&quot;</td>
<td>13' 7&quot;</td>
<td>3'</td>
<td>4&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Double Monitor 15ft Wide</td>
<td>11' 6 3/4&quot;</td>
<td>13' 7&quot;</td>
<td></td>
<td>4&quot;</td>
</tr>
<tr>
<td></td>
<td>30 ft.</td>
<td>Single Monitor 30ft Wide</td>
<td>10' 6 3/4&quot;</td>
<td>13' 7&quot;</td>
<td></td>
<td>4&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Double Monitor 15ft Wide</td>
<td>11' 6 3/4&quot;</td>
<td>13' 7&quot;</td>
<td></td>
<td>4&quot;</td>
</tr>
<tr>
<td>Monitors with minimum light-wells</td>
<td>30 ft. &amp; 60 ft.</td>
<td>Double Monitor 15ft Wide</td>
<td>Low End: 8'</td>
<td>Low End: 13'7&quot;</td>
<td>1'</td>
<td>8&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2&quot;</td>
<td></td>
<td>5/4&quot;(vertical)+ 4'(tapered)</td>
<td></td>
</tr>
<tr>
<td>Skylights</td>
<td>30 ft.</td>
<td>Un-integrated Deep System</td>
<td>8'</td>
<td>13' 7&quot;</td>
<td>5' 7&quot;</td>
<td>6' 1/2&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integrated Shallow System</td>
<td>10'</td>
<td>13' 7&quot;</td>
<td>3' 7&quot;</td>
<td>6' 1/2&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extended Splays</td>
<td>Low point on the ceiling: 9&quot;</td>
<td>13' 7&quot;</td>
<td>4' 7&quot;</td>
<td>6' 1/2&quot;</td>
</tr>
</tbody>
</table>
4.2. RESEARCH METHOD

This section discusses the research approach for the proposed study and focuses on the research method. Computer simulation is the method utilized to conduct this research. The analysis is performed in several stages. The roof daylighting models were drawn in Rhinoceros. DIVA-for-Rhino was used for daylighting and whole-building simulation. DIVA 2.0 is a plug-in to Rhino that exports scene geometries, material properties, and sensor grids into the format required to enable the use of Radiance, DAYSIM and EnergyPlus (Lagios et al. 2010). Radiance (Ward, 1994) and DAYSIM (Reinhart and Walkenhorst, 2001) are validated simulation tools for daylighting.

(1) Illuminance distribution across the task surface is computed for a single moment in time using Radiance. (2) Annual interior illumination is assessed using DAYSIM. (3) Whole-building energy simulation is performed with EnergyPlus. (4) Operating energy is presented for the different categories of use in the building. (5) Total energy operating costs (in dollars) are presented for each daylighting system to make comparisons and suggest design optimizations.

Roof monitors are used with baffles in buildings, however, because of anomalies experienced in Radiance, it is decided to model roof monitors only with diffuse glass and disregard interior light-distributing elements such as baffles.

4.2.1. Daylighting Simulation Inputs

Radiance and DAYSIM was used via DIVA-for-Rhino plug-in. Simulation inputs are explained in this chapter.

4.2.1.1. Simulation Time

Single-point-in-time simulations were conducted at 12 pm on equinox, September 21, with sunny sky condition. Sunny sky condition was preferred over overcast sky condition, because light variations inside spaces were important to be plotted in the worst-case scenario, which is a sunny outdoor condition. Since the glazing material selected for south-facing apertures are diffuse materials, symmetrical illuminance levels are expected in all models. Selecting equinox for simulation day and 12pm for simulation time was a strategy to depict an intermediate lighting condition through a year and a day.
4.2.1.2. Sensor Locations

The simulated space is an office open workspace with 300-lux illuminance target, which provides suitable lighting condition for computer-based work according to the Illuminating Engineering Society (IES).

There are 25x25 nodes at task level with 2.5’ distance from floor in each model to collect illuminance data from Radiance simulation program. Electric lighting control sensors are located in nodes with minimum value of illuminance in a module in order to provide light when occupants start to require electric lighting when illuminance level falls lower than 300 lux in those points. The purpose is to ensure enough light in all spots; therefore, the sensors are located in points with worst daylighting conditions.

**Skylights**

In square skylights with array of 2x2 square openings, 25 sensors are located on a diagonal axis that captures the maximum illuminance underneath the skylights and the minimum illuminance at the center of the model. The electric lighting control sensor is located in the middle of the space, because that is the node with minimum light levels (figure 5A). In linear skylights with two linear apertures, 25 sensors that measure illuminance are located on a north-south axis at the center of the model. The electric lighting control sensor is located at the center where the least illuminance is received.

**Monitors**

In both single and double monitors, 25 sensors that measure illuminance are located on a north-south axis at the center of the models. Single monitors have an electric control sensor at the boundary of the model, located on the middle north-south axis. This point receives the least illuminance at single monitors. Double monitors have an electric lighting control sensor located at the middle of the models (figure 5C and 5D).
4.2.1.3. Electric Lighting Control

Electric lighting is a continuous dimming control system that controls 100% of lighting fixtures in the module. Figure 3 shows the power input percentage of lighting fixtures as a function of available illuminance level at sensor location. EnergyPlus multiplies percentage of lighting power input by the electric lighting density to calculate electric consumption for interior lighting.

In simulations, the standby power is assumed to be zero rather than the typical 20%-30% power driven for dimming control for fluorescent luminaires (figure 3). The assumption is made based on emerging improvements in the field of LED lighting, which enables much lower powers when enough daylight is available.
4.2.1.4. Radiance Parameters

Reasonable output from Radiance depends strongly on correct configuration of input parameters. In general, the Radiance parameters can be split into six groups:

1. **View**: regarding the viewing position, direction etc.
2. **Pixel**: pixel sampling and frequency
3. **Direct**: source sampling and subdivision, specular threshold
4. **Ambient**: frequency and level of sampling in ambient calculation
5. **Participating media**: consideration of mist, turbidity etc.
6. **Miscellaneous**: network controls, file naming, reports etc (Lash 2004).

The indirect component of lighting or the ambient lighting is the most important parameter in daylighting research because it controls daylight received from the sky dome and inter-reflections inside a space. The key elements in Radiance daylighting simulation are:

1. **Ambient bounces** (ab)
2. **Ambient division** (ad)
3. **Ambient supersample** (as)
4. **Ambient resolution** (ar)
5. **Ambient accuracy** (aa)

The effect on accuracy and processing cost of each of these parameters are explained in a PhD thesis (Lash 2004). In that study, Radiance was used to simulate daylight in existing buildings. Radiance parameters are tuned for two buildings with atrium roofs, which are analogous to the roof daylighting systems modeled for the current study in terms of position of the glazing materials. The author calculated the relative error by comparing illuminance levels estimated at analysis grid in Radiance.
and measured illuminance levels in real buildings. The relative error generated by the choice of different Radiance parameters were investigated and a setting that ascertains to yield accurate results for atrium is suggested.

Ambient bounces define maximum number of inter-reflections between surfaces the program calculates before returning to the ambient value. In other words, if the –ab is set to eight, sampling of a ray could occur at eight separate surfaces after leaving the source of light. Ambient bounces can be set from 0 to 8. The lower the –ab value, the less accurate results are yield, and the lower illuminance is calculated at a certain point. The reason is that calculation stops at lower –ab values well before all the light flux has been accounted for. However, setting –ab on maximum possible value could be significantly time consuming (Lash 2004).

In modeling the roof atrium, convergence of calculations occurred at –ab 5. However, in the current study, higher value of –ab is expected. The grid analysis is located deeper within the space than it was in the atrium study. Therefore, it is required to account for more inter-reflections. In addition, having a diffuse material rather than clear material in the model necessitates higher –ab value. The reason is that light is distributed evenly from the diffuse glazing material into the interior space; indirect light from interior surfaces is a major component of the illuminance received at a certain point. As a result, higher ambient bounces should be simulated to reach accuracy in illuminance calculations.

Ambient division defines the number of samples sent out from each sample hemisphere. The square root of this parameter is inversely proportional to the error in the Monte Carlo calculation of indirect illuminance. In other words, more accurate results are yield with higher values of –ad. Ambient supersample (-as) is set at a quarter of –ad. A setting of -ad 512 and –as 128 was confirmed to yield sufficiently accurate results for the atrium study models (Lash 2004).

Ambient accuracy (-aa) is the maximum error permitted in the indirect irradiance interpolation that ranges from 0 to 1. As an instance, –aa 0.1, which is the recommended value in the Radiance website, means that the maximum permitted error is 10%. The lower the value, the more accurate the results will be, but at a huge time cost. Doubling the accuracy tripled the time taken for simulations in the case of atrium, therefore, a value of 0.1 is recommended (Lash 2004).

Ambient resolution (-ar) depends on the ambient accuracy, the scene size and the cut-off point at which further hemispherical sampling stops and interpolation begins.

- \( S_{\text{min}} = \alpha \cdot D_{\text{max}} / \alpha_r \)
• $S_{\text{min}}$ = minimum distance between sample points
• $D_{\text{max}}$ = maximum scene dimension

To achieve accurate and yet fast simulations in the current study, two sets of Radiance parameters were tested for horizontal apertures and four sets of Radiance parameters were tested for vertical apertures. Simulations were conducted at a single point in time at noon September 21. In these sets of parameters, the Radiance program calculates different levels of ambient bounces (ab), ambient divisions (ad), ambient supersample (as), ambient resolution (ar), and ambient accuracy (aa) from lower to higher levels. All the simulation parameters started at higher values than the recommended values in Radiance website (Ward) and the PhD study on atriums (Lash 2004). Higher parameters create more accurate results; however, choosing those high parameters requires long simulation time of approximately twenty hours per simulation.

**Horizontal Apertures:** single-point-in-time daylight simulations in Radiance were conducted with two sets of parameters. Figure 7 shows the illuminance distribution at the diagonal axis of a 30ft x 30ft module with square apertures with 5.5% AFR at task level in Boston. Convergence of Radiance calculations is achieved after simulating two sets of parameters and a smooth curve is generated that represents the illuminance distribution pattern in the space. Reasonable results for the case of horizontal apertures is achieve by setting Radiance parameters at: $ab$ 8, $ad$ 3600, as 900, $ar$ 600, and $aa$ 0.05.

### Table 9 Illuminance results from testing various Radiance parameters for skylight models

<table>
<thead>
<tr>
<th>Horizontal Apertures</th>
<th>Daylighting Parameters</th>
<th>Minimum Illuminance in Diagonal Axis at Task Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ab</td>
<td>ad</td>
</tr>
<tr>
<td>Set 1</td>
<td>7</td>
<td>2500</td>
</tr>
<tr>
<td>Set 2</td>
<td>8</td>
<td>3600</td>
</tr>
</tbody>
</table>
Vertical Apertures: single-point-in-time daylight simulations in Radiance were conducted with four sets of parameters. Figure 8 and 9 show the illuminance distribution at the middle axis of a 30ft x 30ft module with single monitor and double monitors with 20% AFR at task level in Boston. In case of vertical apertures, higher simulation parameters are required to achieve convergence in Radiance calculations and reach a smooth curve for illuminance distribution in the space. The reason is that inter-reflections between interior surfaces play a more important role in roof monitors than skylights. Therefore, accurate illuminance relies on higher ambient parameters in case of roof monitors.

<table>
<thead>
<tr>
<th>Vertical Aperture</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>7 7</td>
<td>2500 625</td>
<td>300 0.05</td>
<td>1660</td>
<td>2284</td>
<td>-3.64</td>
<td>-8.67</td>
<td></td>
</tr>
<tr>
<td>Set 2</td>
<td>8 8</td>
<td>3600 900</td>
<td>600 0.05</td>
<td>1669</td>
<td>2354</td>
<td>-2.98</td>
<td>-4.97</td>
<td></td>
</tr>
<tr>
<td>Set 3</td>
<td>8 8</td>
<td>4624 1156</td>
<td>900 0.05</td>
<td>1673</td>
<td>2359</td>
<td>-2.79</td>
<td>-3.49</td>
<td></td>
</tr>
<tr>
<td>Set 4</td>
<td>8 8</td>
<td>5184 1296</td>
<td>1200 0.03</td>
<td>1703</td>
<td>2342</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 10 Illuminance results from testing various Radiance parameters for roof monitors models
Specifically, double monitors require higher ambient parameters due to more interior surfaces and therefore more inter-reflections. Table 10 shows four sets of Radiance parameters selected for point-in-time simulations, consecutive illuminance results at certain points in the space, and relative errors associated with each set.

The minimum distance between sample points changes at each set of Radiance parameters according to ambient accuracy and ambient resolution (table N).

- $S_{\text{min}} = aa \cdot D_{\text{max}} / \alpha \gamma$
• $D_{\text{max}}$ = maximum scene dimension = 90 ft
• $S_m$ = minimum distance between sample points

*Table 11 Minimum distances between sample points in four sets of Radiance parameters*

<table>
<thead>
<tr>
<th>Radiance Parameter Settings</th>
<th>ar</th>
<th>aa</th>
<th>$S_{\text{min}}$ (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>300</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>Set 2</td>
<td>600</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>Set 3</td>
<td>900</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Set 4</td>
<td>1200</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Convergence of Radiance calculations is achieved after simulating four sets of parameters and a smooth curve is generated at the fourth set with $ab$ 8, $ad$ 5184, $as$ 1296, $ar$ 1200, and 0.03, which required about 30 hours of simulation for a single point-in-time simulation. In this set of parameters, the minimum distance between sample points is 0.03 inch, which is accurate for the purpose of the current research. This simulation is defined as the baseline for estimating the relative error in other simulations based on the following formula:

$$\text{RER} = \frac{(I_{\text{calculated}} - I_{\text{baseline}})}{I_{\text{baseline}}}$$

**RER:** relative error to baseline

$I_{\text{calculated}}$: Illuminance calculated by Radiance at a point

$I_{\text{baseline}}$: Illuminance calculated by the highest set of parameters

Reasonable results for the case of single monitors were achieved by setting Radiance parameters at: $ab$ 8, $ad$ 3600, $as$ 900, $ar$ 600, and 0.05, with -2.98% estimated relative error compared to the baseline (minus shows that the illuminance levels were less than the baseline illuminance levels). For double roof monitors, reasonable results were achieved at $ab$ 8, $ad$ 4624, $as$ 1156, $ar$ 900, and 0.05 with -3.49% estimated relative error from the baseline.

**Climate-based simulation:** Choosing accurate simulation parameters becomes crucial in annual daylight analysis, where it is decided whether electric light is required based on illuminance levels at
a sensor’s location in a space. Since having high parameters for annual calculations is computationally expensive, lower parameters than the point-in-time simulations were selected.

The sensor that controls the electric lighting system is located in the spot that receives the minimum illuminance in each case; in single monitors, this spot is the first node in the middle axis of a square nodal grid, towards the south. In horizontal apertures and double roof monitors, minimum illuminance occurs at the center of a 25x25 nodal grid. This node is the 13th node of either a diagonal axis in square skylights or the 13th node the middle north-south axis in roof monitors.

For horizontal apertures, the first set of Radiance parameters with ab 7, ad 2500, as 625, ar 300, and 0.05 were selected because of achieving convergence in simulation results as depicted in Figure 6. Vertical apertures were more challenging to yield a smooth curve in presenting their illuminance distribution pattern as discussed in previous section.

Table 10 shows that the difference between the first and fourth sets of Radiance parameters in the illuminance received at sensors locations is 43 lux in case of single monitors; in double monitors this difference is slightly raised to 58 lux. This set of parameters with ab 7, ad 2500, as 625, ar 300, and 0.05 were also selected for roof monitors because higher parameters required about 48 hours for each simulation. We should remember that possibility of error is higher in case of double monitors than single monitors due to larger number of interior surfaces and inter-reflections.

4.2.2. Whole- Building Energy Simulation Inputs

The thermal models were generated along with the daylight models in Rhino, with the same dimensions but less architectural details and in a separate layer. DIVA generates the idf file, which contains geometric information of the models. The idf file is modified in EnergyPlus 7.0.0.036 and further parameters such as construction materials, internal loads, operation schedules, and HVAC system were inserted.

Annual interior illuminances were measured by DAYSIM in different models during the daylighting simulation. Electric lighting schedules, generated in format of Excel CSV files from DAYSIM, are the most important inputs to EnergyPlus to assess electric light savings due to the use of natural light.

The simulated space is an open workspace office, which is occupied from 8am until 5pm during weekdays. The first day of the simulation year is a Monday and daylight saving time (DST) is
considered in simulation process. By default, the daylight saving time (DST) in EnergyPlus starts from the first Sunday of April and lasts until the last Sunday of October. U.S. holidays are not defined in the E+ simulation in order to find a clear pattern during weeks when results are analyzed.

4.2.2.1. Thermal Zones

Skylights: skylights were modeled in Rhino with 30’x30’ floor plan and 13’ 7” height from finished floor to the upper edge of the curb supporting the daylight glazing; models were exported to idf format with the use of DIVA-for-Rhino plug in, which translates geometric information from Rhino to idf to be readable in E+. The idf files were inserted in E+ and further parameters such as internal loads, air circulation, and HVAC system were added to them.

Roof monitors: The same process was repeated for roof monitors. Roof monitors are often designed with baffles to diffuse the beam sunlight and avoid glare, however, because of anomalies experienced in Radiance, it was decided to model roof monitors only with diffuse glass and disregard interior light-distributing elements such as baffles. Similarly in energy simulation in E+, roof monitors are modeled with diffuse glazing material and no interior baffles or banners.

All the 30’x30’ modules were simulated as a single thermal zone because the module is representing a well-insulated large office building with four adiabatic walls and an adiabatic ground. As a result, a single zone is modeled to resemble such an interior space that does not have large temperature differences in different locations. In such spaces, the mean temperature is the same all over the place. An exception to this rule is very tall atriums, in which large temperature difference occurs along the volume of daylit atrium.

4.2.2.2. Internal Loads

The installed lighting power density for the building was modelled as 0.9 Watt/ft² (9.68 Watt/m²) based on ASHRAE 90.1-2010 for commercial buildings. Office equipment for each module composed of four computers, a printer, a scanner and a copier, resulting in 886 watts heat generation. Four people occupied each thermal zone during weekdays from 9 am until 5 pm and required total 80 cfm ventilation (ASHRAE 90.1-2010). No air infiltration existed in the models because of having four adiabatic walls.
Table 12 Internal loads generated by interior lights

<table>
<thead>
<tr>
<th></th>
<th>[Btu/h]</th>
<th>[W/ft²]</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting power density</td>
<td>3.07</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Total lights heat gain</td>
<td>2762</td>
<td>810</td>
<td></td>
</tr>
</tbody>
</table>

Table 13 Internal loads generated by occupants

<table>
<thead>
<tr>
<th>Number of people</th>
<th>[#]</th>
<th>4</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible heat gain per person</td>
<td>[Btu/h]</td>
<td>245</td>
<td>W</td>
</tr>
<tr>
<td>Latent heat gain per person</td>
<td>[Btu/h]</td>
<td>155</td>
<td>W</td>
</tr>
<tr>
<td>Total heat gain per person</td>
<td>[Btu/h]</td>
<td>450</td>
<td>W</td>
</tr>
<tr>
<td>Total people heat gain - sensible</td>
<td>[Btu/h]</td>
<td>980</td>
<td>W</td>
</tr>
<tr>
<td>Total people heat gain - latent</td>
<td>[Btu/h]</td>
<td>620</td>
<td>W</td>
</tr>
<tr>
<td>Total people heat gain</td>
<td>[Btu/h]</td>
<td>1800</td>
<td>W</td>
</tr>
</tbody>
</table>

Table 14 Internal loads generated by Electric Equipment

<table>
<thead>
<tr>
<th>Number of computers &amp; monitors</th>
<th>[#]</th>
<th>4</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printers, scanners, and copiers heat gain</td>
<td>[W]</td>
<td>86</td>
<td>[W]</td>
</tr>
<tr>
<td>Total equipment heat gain</td>
<td>[Btu/h]</td>
<td>3021</td>
<td>[W]</td>
</tr>
</tbody>
</table>

4.2.2.3. Air Circulation

The design space is not naturally ventilated for cooling purposes and outdoor air is only provided to create fresh air in the space based on ASHRAE 90.1 requirements for office spaces.

There is no infiltration in the design space because it is representing a small portion of a large office space; therefore, all the surrounding walls are adiabatic without any connection to outdoors and with no air leakage.

Table 15 Outdoor air requirement calculation for thermal zone

<table>
<thead>
<tr>
<th>Number of people</th>
<th>[#]</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation requirements by ASHRAE 90.1</td>
<td>[cfm/person]</td>
<td>6.5</td>
</tr>
<tr>
<td>Ventilation requirements by ASHRAE 90.1</td>
<td>[cfm/ft²]</td>
<td>0.06</td>
</tr>
<tr>
<td>Total ventilation needed</td>
<td>[cfm]</td>
<td>80</td>
</tr>
<tr>
<td>Ventilation needed</td>
<td>[cfm]/person</td>
<td>20</td>
</tr>
</tbody>
</table>
Specific Volume of Dry Air = 13.3 [ft³/lb]
Dry air mass flow rate \( m = \frac{80 [\text{ft}^3/\text{min}]}{13.3 [\text{ft}^3/\text{lb}]} = 6.01 [\text{lb/min}] = 360.6 [\text{lb/hr}] \)

4.2.2.4. HVAC System

In EnergyPlus, two types of loops should be defined for HVAC system simulation: an air loop and a plant loop.

HVAC Air Loop Components are the followings:
- Outdoor Air Mixing Box
- AC Unit (Cooling Coil)
- Gas Furnace
- Humidifier
- Fan
- Air splitter
- Air terminal with reheat
- Mixing box

The air loop is the major loop that handles air distribution to the zones and incorporates the heating, cooling, and other components of the HVAC system. Air is the transport medium in air loops while plant loop uses other liquid fluids of user's choice.
Plant loop defines heating and cooling components of the HVAC system based on the supply and demand loads. In design of the plan loops, information such as cooling coil supply air temperature and humidity ratio, and cooling coil outlet air temperature were used. Cooling system is an air conditioning system that employs a direct-expansion DX cooling coil with single speed. The AC system runs with electricity with COP (Coefficient of Performance) of 3. Heating system is a furnace that uses natural gas with COP of 0.8.

In the designed HVAC Air Loop, cooling coils perform as heat exchangers with an air and a water side. The air side of the coil is handled within the air loop where the control of the device is also maintained. The fluid side of the coil is handled within the plant demand side, which passes the energy requirements of the coil on to the plant supply side. All loops are simulated together by modeling each side in a particularly calling order. Overall iterations ensure that the results for the current time step are balanced and updated information has been passed to both sides of the plant loops.

Cooling System Design

Peak loads calculations for cooling systems are conducted based on ASHRAE 2010- 0.4% values, which are temperatures not exceeded more than 0.4% of the year or 35 hours per year. Results achieved from peak load calculation will be used to size the cooling equipment; information such as supply air temperature and cooling coil outlet temperature will be inputs in EnergyPlus. In addition to peak loads calculation, annual calculation of cooling loads will be conducted via simulation in EnergyPlus.

Based on ASHRAE 2010- 0.4% values, in Boston, dry bulb temperature is 90.8 F with a coincident wet bulb of 73.5F and dew point of 69 F. In Miami, dry bulb temperature is 91.8 F with a coincident wet bulb of 77.6 F and dew point of 75 F. Peak cooling loads calculations were conducted for 30’x30’ modules with 7% AFR skylights in Boston and Miami; results show that sensible Heating Factor (SHF) is 0.81 and 0.74 in Boston and Miami respectively.
Cooling coils outlet air temperature and supply air temperatures could be measured from the psychrometric chart. The following tables show those design information for Boston and Miami.

### Table 16 Cooling system requirement for Boston, MA

<table>
<thead>
<tr>
<th>State</th>
<th>Node</th>
<th>$T_{db}$</th>
<th>RH</th>
<th>$T_{dew}$</th>
<th>Specific Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Air</td>
<td>OUT</td>
<td>90.8</td>
<td>49%</td>
<td>69</td>
<td>0.0153</td>
</tr>
<tr>
<td>Cooling Coil</td>
<td>A</td>
<td>54</td>
<td>100%</td>
<td>54</td>
<td>0.0088</td>
</tr>
<tr>
<td>Outlet Air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Air</td>
<td>B</td>
<td>65</td>
<td>67%</td>
<td>50</td>
<td>0.0088</td>
</tr>
<tr>
<td>Inside Zone Air</td>
<td>IN</td>
<td>75</td>
<td>50</td>
<td>55</td>
<td>0.009</td>
</tr>
</tbody>
</table>
Table 17 Cooling system requirement for Miami, FL

<table>
<thead>
<tr>
<th>State</th>
<th>Node</th>
<th>T&lt;sub&gt;db&lt;/sub&gt;</th>
<th>RH</th>
<th>T&lt;sub&gt;dew&lt;/sub&gt;</th>
<th>Specific Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Air</td>
<td>OUT</td>
<td>91.8</td>
<td>59%</td>
<td>75</td>
<td>0.0188</td>
</tr>
<tr>
<td>Cooling Coil Outlet Air</td>
<td>A</td>
<td>53</td>
<td>100%</td>
<td>53</td>
<td>0.0084</td>
</tr>
<tr>
<td>Supply Air</td>
<td>B</td>
<td>65</td>
<td>65%</td>
<td>53</td>
<td>0.0084</td>
</tr>
<tr>
<td>Inside Zone Air</td>
<td>IN</td>
<td>75</td>
<td>50</td>
<td>55</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Table 18 Peak cooling loads calculation in Boston and Miami

<table>
<thead>
<tr>
<th>COOLING LOAD TOTALS</th>
<th>Units</th>
<th>Boston</th>
<th>Miami</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td>[Btu/h]</td>
<td>1,600</td>
<td>1,600</td>
</tr>
<tr>
<td>Lights</td>
<td>[Btu/h]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Equipment</td>
<td>[Btu/h]</td>
<td>3,021</td>
<td>3,021</td>
</tr>
<tr>
<td>Envelope - construction walls</td>
<td>[Btu/h]</td>
<td>6,863</td>
<td>7,136</td>
</tr>
<tr>
<td>Envelope - conduction roof</td>
<td>[Btu/h]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Infiltration</td>
<td>[Btu/h]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation</td>
<td>[Btu/h]</td>
<td>3,812</td>
<td>5,255</td>
</tr>
<tr>
<td>Total cooling load</td>
<td>[Btu/h]</td>
<td>15,296</td>
<td>17,012</td>
</tr>
<tr>
<td>Total cooling load/unit area</td>
<td>[Btu/h-ft&lt;sup&gt;2&lt;/sup&gt;]</td>
<td>17.0</td>
<td>18.9</td>
</tr>
<tr>
<td>Total sensible cooling load</td>
<td>[Btu/h]</td>
<td>12,237</td>
<td>12,598</td>
</tr>
<tr>
<td>Total latent cooling load</td>
<td>[Btu/h]</td>
<td>3,059</td>
<td>4,415</td>
</tr>
</tbody>
</table>

| Sensible Heating Factor | 0.80 | 0.74 |

Ventilation Loads and Required Air Conditioning: From the psychrometric chart, total loads required for ventilation is calculated. These numbers are close to the ventilation loads calculated in cooling loads hand calculations.

Table 19 Ventilation requirement in Boston and Miami

<table>
<thead>
<tr>
<th>Ventilation Loads</th>
<th>Unit</th>
<th>Boston</th>
<th>Miami</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta H (H out-H in)</td>
<td>[Btu/lb]</td>
<td>37.7-27=10.5</td>
<td>43-27=16</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>[lb/hr]</td>
<td>338</td>
<td>335.2</td>
</tr>
<tr>
<td>Total Loads for ventilation from psychrometric chart (Sensible+ latent)</td>
<td>[Btu/hr]</td>
<td>3,549</td>
<td>5,363</td>
</tr>
<tr>
<td>Total Loads for ventilation</td>
<td>[Btu/hr]</td>
<td>3,812</td>
<td>5,255</td>
</tr>
</tbody>
</table>

Air condition required in Boston: 15,296 [Btu/hr]/12,000 [Btu/ton-hr]= **1.274** tons air conditioning for a 900 ft<sup>2</sup> space

Air condition required in Miami: 17,012 [Btu/hr]/12,000 [Btu/ton-hr]= **1.418** tons air conditioning for a 900 ft<sup>2</sup> space
Heating System Design

Peak loads calculation for heating systems were conducted based on ASHRAE 2010 99.6% values, which are temperatures exceeded more than 99.6% of the year or 8725 hours per year. Results achieved from peak loads calculation will be used to size the heating equipment; information such as supply air temperature and cooling coil outlet temperature will be inputs in EnergyPlus. In addition to peak load calculation, annual calculation of heating loads will be conducted via simulation in EnergyPlus.

Based on ASHRAE 2010 99.6% values, in Boston, dry bulb temperature is 7.4 F; in Miami, dry bulb temperature is 47.7 F. Peak cooling loads calculations was conducted for 30’x30’ modules with 7% AFR skylights in Boston and Miami. In Boston, a humidifier is required in the HVAC air loop to provide the required thermal condition inside (heating set point: 71.6 F, 50% RH, and 0.008 HR) due to the very low dry bulb temperatures outside (7.4F). In that condition, even with increasing the size of a plant, comfort condition cannot be met indoors.

Table 20 Heating peak load calculation

<table>
<thead>
<tr>
<th>Heating Peak Load Calculation</th>
<th>Boston</th>
<th>Miami</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Base on ASHRAE 90.1 99.6% Design Data, for building envelope with skylights with AFR 5.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside Mean Air Temp</td>
<td>71.6</td>
<td>71.6</td>
</tr>
<tr>
<td>Outside Temperature</td>
<td>7.4</td>
<td>47.7</td>
</tr>
<tr>
<td>Delta T [F]</td>
<td>64.2</td>
<td>23.9</td>
</tr>
<tr>
<td>Internal Load</td>
<td>Assumed</td>
<td>0</td>
</tr>
<tr>
<td>Opaque Roof Area [ft²]</td>
<td>836</td>
<td>836</td>
</tr>
<tr>
<td>U-value [Btu/ft².F]</td>
<td>0.033</td>
<td>0.033</td>
</tr>
<tr>
<td>Conductive Heat Loss through Opaque Roof [Btu/h]</td>
<td>1771.15</td>
<td>659.35</td>
</tr>
<tr>
<td>Skylights</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area [ft²]</td>
<td>64.00</td>
<td>64.00</td>
</tr>
<tr>
<td>U-value [Btu/ft².F]</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td>Conductive Heat Loss through Glazing part of Roof [Btu/h]</td>
<td>2629.63</td>
<td>978.94</td>
</tr>
<tr>
<td>Ventilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Required Air Volume [cfm]</td>
<td>74.00</td>
<td>74.00</td>
</tr>
<tr>
<td>Ventilation Sensible Heat Loss [Btu/h]</td>
<td>5225.88</td>
<td>1945.46</td>
</tr>
<tr>
<td>TOTAL HEATING LOADS [kBtu]</td>
<td>9626.66</td>
<td>3583.76</td>
</tr>
<tr>
<td>TOTAL HEATING LOADS per Sqft [kBtu/ft²]</td>
<td>10.70</td>
<td>3.98</td>
</tr>
</tbody>
</table>
In Boston, outside air is humidified by an electric humidifier to reach 0.008 HR and then air is heated by a gas furnace to 71.6 F. Humidifier has 0.06 GPM (Gallon per Meter) capacity and 1 kW/h power. Calculations for humidifier capacity and power are shown in table 21 and 22.

Table 21 Humidifier Capacity

<table>
<thead>
<tr>
<th>Lowest Humidity Ratio</th>
<th>Required Humidity Ratio</th>
<th>lbw/lba</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>lbw/lba</td>
</tr>
<tr>
<td>Air Loop Outdoor Air Flow Rate</td>
<td>6</td>
<td>lb/min</td>
</tr>
<tr>
<td>Required Steam Flow Rate</td>
<td>6*0.008=0.048</td>
<td>lbw/min</td>
</tr>
</tbody>
</table>

8.34 lbw = 1 gallon

<table>
<thead>
<tr>
<th>Required Steam Flow Rate</th>
<th>Humidifier Capacity</th>
<th>gal/min (GPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.048/8.34=0.0058</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>0.01*60= 0.6</td>
<td>0.01*60= 0.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 22 Humidifier Power

<table>
<thead>
<tr>
<th>Steam Flow Rate</th>
<th>Work Required for Steam with P=100 psig with feedwater temperature 50 °F</th>
<th>lbw/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.048*60=2.88</td>
<td>0.3492</td>
<td>kW/lbw</td>
</tr>
<tr>
<td>Humidifier Power</td>
<td>2.88*0.3492=0.97</td>
<td>kW/hr</td>
</tr>
</tbody>
</table>

Outdoor Air Mixing Box

The space is not naturally ventilated for cooling purposes and outdoor air is only provided to create fresh air in the space based on ASHRAE 90.1 requirements for office spaces.

A mixed air box is controlled by Controller: OutdoorAir in EnergyPlus simulation. The purpose of the outdoor air controller is to provide outdoor air for ventilation and also provide free cooling whenever possible with the use of economizer. For this project, the outdoor air controller is only responsible for providing the required fresh air for ventilation in the space.

AirLoopHVAC Outdoor Air Mass Flow Rate is 6.01 [lb/min] in simulation, which is the same number acquired from hand calculations. Outdoor air mass flow rate is constant at 6.01 [lb/min] when the fan is on. Schedule of the fan operation could be found in the operation controls section.
The OutdoorAir: Mixer is a component used in an outdoor air system. The outdoor air mixer takes in two streams of air: the system return air and the outdoor air.

4.2.2.5. HVAC Operation Controls

Operation Schedules

On weekends, Saturdays and Sundays, the office building is unoccupied, thus, weekends have different schedules in occupancy and HVAC system management. Occupied hours are 9 am until 5 pm every weekday; HVAC operation schedule, and fan availability, and heating and cooling setback and setpoint temperatures are shown in tables 23 and 24.

<table>
<thead>
<tr>
<th>Table 23 HVAC Operation Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>01/01 - 03/31</strong></td>
</tr>
<tr>
<td><strong>04/01 - 09/30</strong></td>
</tr>
<tr>
<td><strong>10/01 - 12/30</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 24 Fan Availability Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>01/01 - 03/31</strong></td>
</tr>
<tr>
<td><strong>04/01 - 09/30</strong></td>
</tr>
<tr>
<td><strong>10/01 - 12/30</strong></td>
</tr>
</tbody>
</table>

Temperature and Humidity Controls

Temperature is controlled by a dual thermostat, which works based on two operation schedules in heating seasons and cooling seasons. The thermostat works based on the operative temperature, which accounts for mean radiant temperature of the space. Operation temperature is defined as combination of 55% mean radiant temperature and 45% mean air temperature. In other words: $T_{opt} = 0.55 \text{MRT} + 0.45 \text{Mean Air Temp}$. Heating and cooling setback and setpoint temperatures are shown in table 25.

<table>
<thead>
<tr>
<th>Table 25 Heating and cooling setback and setpoints</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heating Setpoint</strong></td>
</tr>
<tr>
<td>0:00- 4:00</td>
</tr>
<tr>
<td>4:00- 19:00</td>
</tr>
<tr>
<td>20:00-24:00</td>
</tr>
</tbody>
</table>
The humidifier designed for Boston is controlled based on the schedule showed in table 26 with 35% minimum relative humidity setpoint in the space. In both Boston and Miami, dehumidification is processed with the setpoints shown in table 27.

Table 26 Humidifier schedule

<table>
<thead>
<tr>
<th>Date</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/01 - 04/15</td>
<td>6:00 - 18:00 On, Other Off</td>
</tr>
<tr>
<td>04/16 - 09/30</td>
<td>Always Off</td>
</tr>
</tbody>
</table>

Table 27 Humidification and dehumidification setpoints

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Humidifying Setpoint</th>
<th>Dehumidifying Setpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00 - 12:00</td>
<td>35%</td>
<td>0:00 - 5:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5:00 - 18:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18:00 - 24:00</td>
</tr>
<tr>
<td>90%</td>
<td></td>
<td>60%</td>
</tr>
</tbody>
</table>

Setpoint Managers

There are three Setpoint Manager: Mixed Air in the air loop are located after these three components: Outdoor Air Controller, Air Loop Cooling Coil, and Air Loop Heating system. One Setpoint Manager: Reheat is located at the fan outlet node.

4.2.3. Glare Analysis Inputs

Daylighting systems have been overridden after being implemented in many buildings when they cause glare for occupants even at a short period of time. A common response to this kind of glare is to close drapes that are available or turn up the lights in order to even out illumination and reduce the contrast. Therefore, the purpose of this study is to investigate the problem caused by glare in the proposed roof daylighting systems.

Evalglare, which is an engine for calculation of Daylight Glare Probability (DGP), is used through the use of DIVA-for-Rhino plug in (for more information about DGP see section 2.1.4. Daylighting Performance Metrics). First, a 180° fish eye camera generates an image of the space by Radiance
simulation tool. Evalglare applies the DGP formula to calculate probability of glare at each point of a space from the generated two-dimensional image.

Models were exactly the same models used in daylighting simulation drawn with Rhino 3D modeling tool. Square skylights were selected among horizontal roof daylighting systems and single roof monitors facing north-south were selected among vertical roof daylighting systems. The reason was to focus on the worst-case scenario. Square apertures are more challenging than linear apertures, single roof monitors are more challenging than double roof monitors because in these two cases, probability of glare is higher because a large area of glazing is localized in the space. Square apertures have 5.5% Aperture to Floor Area Ratio (AFR) and single roof monitors have 25% AFR. In square skylights, two shapes of light-wells were examined for glare analysis: skylights with un-integrated system and squared-off light-wells, and skylights with integrated systems and beveled light-wells (more information are provided in building parameters in section 4.2.2.1). The location of models in glare analysis is Boston.

Experience shows that roof monitors with diffuse glass have glare problem at some points in the space, therefore, to closely analyze and solve this problem a strategy is made for glare analysis. First, illuminance values are measured at Sept 21 at noon for single roof monitors with 25% AFR facing north and south. North facing apertures has a clear glass and the south facing apertures is diffuse glazing (lighting properties of material in roof monitors are explained in section 4.2.2.2). Second, glare analysis is conducted with DIVA-for-Rhino Evalglare tool. Third, two suggestion are made to improve visual comfort in that special case including baffles (series of parallel reflective pieces) and a banner (one hanging piece of cloth). When daylighting solutions are implemented, probability of glare is assessed to investigate improvement of daylighting performance of the roof monitors. Fourth, the impact that adding baffles and banners have on illuminances at task level are assessed by conducting a single-point illuminance evaluation with Radiance in DIVA-for-Rhino for both cases with baffles and banners.

4.2.3.1. Location of Glare Assessment

Horizontal Apertures: In case of skylights, the worst locations with highest chance of glare were chosen to assess Daylight Glare Probability (DGP) assessment. In the Rhino model, a camera is located underneath a skylight at task surface, 2.5’ above the floor. The camera is facing towards the skylights with 85° angle from the horizontal surface targeting the center of the skylight.
Vertical Apertures: In case of monitors, the worst locations with highest chance of glare were chosen for Daylight Glare Probability (DGP) assessment. In the Rhino model, a camera is located at task surface, 2.5’ above the floor. In the Rhino model, a camera is located underneath a skylight. The camera is facing south towards the center of the roof monitor with 45° angle from the horizontal surface targeting the header of the glazing surface.

4.2.3.2. Time and Weather Condition

Glare analysis is conducted first for a single-point-in-time, which is the worst-case scenario for each of the roofing configurations. Second, annual daylighting glare probability is conducted for investigation of the performance of daylighting systems throughout a year.

Horizontal Apertures: simulation for glare analysis is conducted at noon June 21, when solar incidence has an almost normal angle to the horizontal apertures. Sunny sky condition is simulated to account for the worst case in terms of probability of glare.

Vertical Apertures: simulation for glare analysis is conducted at noon September 21 for vertical monitors facing south-north in sunny sky condition to account for the worst case in terms of probability of glare.

4.2.3.3. Radiance Parameters

Radiance parameters were tested to reach an accurate level of results for the case of roof-daylighting systems. The size of image is 3000x3000 for all images generated in Radiance. Some important simulation parameters are the followings: Direct Pretest Density (dp) 512

Ambient Resolution (ar) 128
Direct Thresholding (dt) 0
Direct Jitter (dj) 0
Limit Weight (lw) 0.000001
Specular Sampling Threshold (st) 0.15
Ambient Accuracy (aa) 0.1
Ambient Division (ad) 2048
Ambient Supersamples (as) 512

<table>
<thead>
<tr>
<th>dp</th>
<th>ar</th>
<th>dt</th>
<th>dj</th>
<th>dr</th>
<th>lr</th>
<th>lw</th>
<th>st</th>
<th>ps</th>
<th>pj</th>
<th>ab</th>
<th>aa</th>
<th>ad</th>
<th>as</th>
</tr>
</thead>
<tbody>
<tr>
<td>512</td>
<td>128</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0.000001</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0.1</td>
<td>2048</td>
<td>512</td>
</tr>
</tbody>
</table>
4.2.3.4. Material Properties

Fabric banners were the materials added to models for glare analysis. Properties of the fabric banners are the followings:

Light Transmittance: 50% (100% diffusive or 100% Haze)

Td (Diffuse Transmissivity)=40%
Ts (Speculat Transmissivity)=0%
Sr (Surface Roughness)=0
Rs (Reflected Specularity)=0
Rd (Diffuse Reflection)= 60%
Cb (Diffuse Reflectance of Blue)=60%
Cg (Diffuse Reflectance of Green)=60%
Cr (Diffuse Reflectance of Red)=60%

Calculations:
A7=Ts/(Td+Ts)=0
A6=(Td+Ts)/(Rd+Td+Ts)=0.4/1=0.4
A5=Sr=0
A4=Rs=0
A3, A2, A1=Cb/((1-Rs)*(1-A6))=0.6/0.6=1

and the material is scripted in Radiance:

Fabric radiance parameters
void trans fabric_50p
0
0
7 1 1 1 0 0 0.4 0
A1 A2 A3 A4 A5 A6 A7

4.3. RESEARCH QUALITY

Internal validity is the most important part to ascertain research quality. Internal validity proves the true value of a causal relation in a research; in other words, it proves that the outcomes of the research, which is energy use in the building, is influenced by changing the independent variables.

In simulation research, validity of both “model” and “computer program” needs to be tested. Validity of modeling is an important issue in evaluating the quality of simulation research. Diva-for-Rhino has
much strength in creating a real-world condition. It provides scripting files to be readable for both RADIANCE and EnergyPlus. By manipulating scriptures in Diva, expanded variety of options for building materials, thermal zones, HVAC systems and other inputs will be available at the modeling stage; as a result, the simulated model in Diva could be considerably akin to the real case situation, which adds to reliability of the research method.

However, simulation research, in general, has some weaknesses in this regard. The weakness of simulation research is the fact that creation of a “complete replication” of the real-world is not definable in an ensured way. Thus, the accuracy of the model is always under question. The models to be made in Diva-for-Rhino are expected to be as close as possible to the real situation. As an instance, modeling building details such as exposed structural details (trusses in case of roof monitors) was not possible. The reason lies in the fact that elaborating the model makes it too complex for the program to calculate the algorithms and the simulation process becomes too time consuming to accomplish. However, in the models, the influence of structural members on lowering daylighting illumination has been accounted for. As a result, the visible transmittance of the glazing material is decreased by a percentage that represents the obstructing effect of the trusses.

The computer program used in this research, Diva-for-Rhino, is designed based on EnergyPlus, which is a prominent software used in building energy analysis arena. Diva-for-Rhino improves the modeling potentials and adds graphic user interface (GUI) to EnergyPlus. Diva also enables daylighting analysis with RADIANCE for Rhino models. As mentioned in chapter 2.2, in building simulation methodologies, both RADIANCE and EnergyPlus are validated simulation tools that are extensively used in the fields of lighting and energy analysis.

Next section outlines the physical daylighting experiment, which was undertaken as the pilot study for this research. Then hand calculations for heating and cooling energy loads for an hour of building operation in sample models will be presented.

4.3.1. Daylighting Physical Experiment
The physical experiment, which was conducted at earlier stages of this Ph.D. study in summer 2010, will be presented in this section supplemented with recommendations for an experiment in future to validate the daylighting results achieved from RADIANCE software. Results from the previous experiment will be compared with simulation results from RADIANCE simulation program in Diva-for-Rhino. The physical models in the physical experiment were identical to the virtual models simulated in Radiance, both representing a space with 30’x30’ floor plan.
The experimental process was designed with the purpose of investigating daylight quantity and variability in case of two roof-daylighting systems configuration including square and linear apertures in flat roofs in Raleigh, NC while answering these research questions:

- How much is illuminance levels on the workplane in a room with square apertures (skylights) and another similar room with linear apertures mounted on a flat roof?
- How much illuminance levels change by changing the area and spacing between apertures in case of square apertures (skylights) and linear apertures mounted on the flat roof of a room?
- How variable are daylight levels in each daylighting configuration?

To answer these questions, physical models were made and tested in a special settings with equipment required to collect and store data. In the experiment, there were only 2 independent variables: “roofing system configurations” and “number and spacing between apertures”. Both linear and circular-localized apertures were tested in the experiment, with a range of 2 to 4 apertures with 10% AFR (Aperture to Floor Area Ratio). However, the discrepancy between the previous experimentation and RADIANCE simulation is the percentage of glazing to floor area (AFR), which changed from 10% in the experiment to 3.5% and 5.5% in simulation. Therefore, we should expect higher illuminances in results the experiment conducted with physical models. The floor plans and sections of the physical models for experiment are presented in figure 12.

![Figure 12](image)

*Figure 12 Floor plans of physical models with 2 and 3 linear apertures. The red line shows five axes, on which illuminance is measured by the sensors (series 1 to 5).*
4.3.1.1. Physical models

In the experiment, the physical models had the same size in floor plan as the virtual model did in Rhino models. However, the height of models differed from 10’ in physical models to 9’ in simulation models. Models for the physical experiment were built to the scale of 1” equal to 4’. For that study, rectangular boxes with 7.5’ length, 7.5’ width, and 2.5’ height were made to represented a space with 30’x30’ dimension in floor plan and 10’ height. For future experiments, it is recommended to double the size of physical models to increase accuracy of the study considering problems that occurred in previous modeling experience when creating small details in the models. Dimensions of the models in the previous experiment are shown in table 29.

| Table 29 Dimensions in linear apertures with 10% AFR (Aperture to Floor Area Ratio) |
|----------------------------------------|------------------|-------------------|--------------------------|
| Edge of entire roof | Number of subdivisions of the overall edge of the roof | Edge of one rectangle of the three rectangles of the roof | Area of each rectangle | Linear apertures 10% |
|---------------------|------------------|-------------------|--------------------------|
| 7.5                 | 2                 | 3.75              | 28.13                    | Area of one linear aperture 2.81 |
|                     |                   |                   |                          | Length of the aperture 7.5 |
|                     |                   |                   |                          | Width of the aperture 0.38 |
| 7.5                 | 3                 | 2.50              | 18.75                    | Area of one linear aperture 1.88 |
|                     |                   |                   |                          | Length of the aperture 7.5 |
|                     |                   |                   |                          | Width of the aperture 0.25 |
One parameter that should be changed as an independent variable for the future study is transmissivity of the glazing material. Previously, sunshades were made to represent a perfect diffuse glazing material for each aperture. Sunshades were positioned to reject beam light and only let diffuse daylight enter the models. The targeted transmissivity for glazing materials is 42% for future experiments. Therefore, it is recommended to provide pieces of white (milky) acrylic with the required transmissivity level for the models. If the exact level of light transmittance of the acrylic sheet is not known, a Daylight Factor test could be conducted, with a simple box with the acrylic sheet on top of an aperture in the box. The DF will be derived from comparing the illuminance level passed through the aperture to the exterior illuminance level in overcast condition. To save time and material for modeling, the acrylic sheet could be located on top of the models without gluing or fixing it to the models; in that case, the acrylic sheet could be easily replaced without the need to make a new set of models.

In the previous study, light reflectance from the model surfaces were 90% from ceiling, 40% from walls, and 60% from floor area. However, to be consistent with the simulated models in Radiance, the reflectances should change in future to 80%, 50% and 20% from ceiling, walls, and floor area respectively. Therefore, we should expect differences in daylight illuminances received on the task surface between experiment and simulation.

One variable in the future study will be the ceiling depth, changing due to integration of structure and ductwork in roof construction. The ceiling depth should be 5’ 7” in case of un-integrated construction and 3’ 7” in case of integrated construction. The other parameter that changes in the skylight configurations will be the splay of lightwells. Two different types of light-wells should be made: skylights with right angle and skylights with 45° splay. In future, the models need to be made with a large scale enough to represent such details. To study the effects that changing the ceiling depth and splaying light-wells have on daylighting the models, larger models are required with larger scale than the previous study (1”=4’).

4.3.1.2. Settings

The site in the previous experiment was the Daylight Research Facility, Raleigh, NC (35° 46' latitude and 78° 39' longitude), which provides good condition for daylighting tests because of relatively low obstructions surrounding the site. The Daylight Research Facility is also equipment with the tools and devices required for the proposed daylighting experiment. This equipment will be explained in the next section.
The experiment was conducted on a sunny day in summer 2010 from 9:30 am to 4:00 pm. It was prudent to choose a summer day, because the larger number of sunshine hours that occur in a summer day allows the whole study to complete in one day. This fact will reduce probable errors in calculations, which occur by changes in the sky condition when the experiment is conducted in two different days. However, future experiments should be consistent with the simulation process, and should be planned to collect data on the same day, which has been equinox (September 21 at 12:00 pm) for the simulations so far.

The location of the experiment and simulations should be consistent. For this study, simulations for Boston, MA and Miami, FL have been conducted but the previous experiment was conducted in Raleigh. Because of this discrepancy, we should expect difference in illuminance levels measured in physical models than the virtual models.

4.3.1.3. Equipment
The tools required for the daylighting experiment are the followings shown in figures 15 and 16:

- Sensors called “photometers” to measure illuminance levels inside the models.
- Shaded photometers to measure outdoor diffuse illuminance.
- One photometer located horizontally, and two located vertically to measure directional illuminances.
- PSP (Precision Spectral Pyranometer), which records solar radiation at each time step. The PSP needs to be shaded to record the diffuse sky radiation.
- Data loggers and Multiplexer to record and save data during the experiment.
- A camera with fish eye imager to take pictures inside the models.
- A “base”, where the models will be located. The base should be designed specific for the certain scale models to provide easy and accurate process of data collection. Three directional photometers, data logger, multiplexer and the camera will attach to the base.
- A computer connected to the data logger to load data and store it.
All the sensors should be calibrated prior to the experiment for quality purposes of the study.

4.3.1.4. Procedure

For testing daylight quantity and variability, first, illuminance levels inside the models should be collected. Each physical model will be located parallel to East-West direction with diffuse acrylic sheets on top of them. In the previous study, five photometric sensors were placed in the middle of the base with 0.625” height from the surface to collect data at work plane inside the models. The reason to have five sensors on the base was the limited length of the models (7.5”) that allowed only five sensors placed from wall to wall in each model. In future, by building larger models, more sensors could be accommodated in the base. It is recommended to locate the sensors on a diagonal axis of the models, where the largest variation of data occurs.

Since the sensors are fixed on the base, the models will be moved along a ruler designed to show spots where data should be collected. The closer the data collection point, the more accurate the results will be. In the previous study, illuminance levels were gained at twenty-four points along the models’ length. It is recommended to adjust the number of these data collection points with the
number of sensors located diagonally inside the model. Since only data on the diagonal axis will be needed and the model will be big enough to accommodate a reasonable number of sensors inside, the model does not need to move in future experiments; all the sensors will be on the base, on a diagonal axis of the models’ floor plan. Data collection will be completed for each model at once without having to move them.

One horizontal sensor will be placed outside the models to collect atmosphere’s illuminance, which is changing due to uneven sky conditions. The north-facing sensor will collect the diffuse sunlight and the south-facing sensor will collect both beam and diffuse daylight from the south direction.

A data logger, which scans and saves data from sensors, will be used as the main device to collect data. Data will be loaded and stored in a computer at the next step.

![Image](image.png)

*Figure 17 Interior of the models; the model is moved in a way that sensors collect data in various points along the model’s length.*

4.3.1.5. Data analysis and results

Data will be collected with the instruments explained and in the order described above. The results will then be exported to Microsoft Excel to generate relevant tables and charts. Table 29 shows an example of result tables in the previous experiment.

To evaluate daylight quantity in different configurations, average illuminance levels at a single point in time is required. Illuminance levels collected from a diagonal axis in the models will be averaged in Microsoft Excel. Daylight variability, which is defined as the maximum to minimum illuminance ratio, will also be calculated in Microsoft Excel.
Table 29 Example of results from the physical experiment

<table>
<thead>
<tr>
<th>3 slots linear aperture</th>
<th>Sensor 1</th>
<th>Sensor 2</th>
<th>Sensor 3</th>
<th>Sensor 4</th>
<th>Sensor 5</th>
<th>north</th>
<th>south</th>
<th>Horizontal sensor</th>
<th>Shadow banded sensor</th>
<th>Solar radiation average rate (kW)</th>
<th>Total Solar radiation (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/21/10 13:36</td>
<td>0.47</td>
<td>0.543</td>
<td>0.56</td>
<td>0.55</td>
<td>0.47</td>
<td>13.03</td>
<td>92.7</td>
<td>81.7</td>
<td>8.68</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
<tr>
<td>10/21/10 13:36</td>
<td>0.483</td>
<td>0.56</td>
<td>0.573</td>
<td>0.563</td>
<td>0.487</td>
<td>13.02</td>
<td>92.5</td>
<td>81.5</td>
<td>8.67</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
<tr>
<td>10/21/10 13:36</td>
<td>0.507</td>
<td>0.58</td>
<td>0.596</td>
<td>0.59</td>
<td>0.503</td>
<td>13.01</td>
<td>92.6</td>
<td>81.4</td>
<td>8.67</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
<tr>
<td>10/21/10 13:36</td>
<td>0.541</td>
<td>0.616</td>
<td>0.64</td>
<td>0.62</td>
<td>0.536</td>
<td>12.99</td>
<td>92.5</td>
<td>81.2</td>
<td>8.68</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
<tr>
<td>10/21/10 13:37</td>
<td>0.576</td>
<td>0.663</td>
<td>0.686</td>
<td>0.663</td>
<td>0.56</td>
<td>13.02</td>
<td>92.8</td>
<td>81.5</td>
<td>8.69</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
<tr>
<td>10/21/10 13:37</td>
<td>0.64</td>
<td>0.736</td>
<td>0.766</td>
<td>0.73</td>
<td>0.61</td>
<td>13.01</td>
<td>92.8</td>
<td>81.5</td>
<td>8.69</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
<tr>
<td>10/21/10 13:37</td>
<td>0.716</td>
<td>0.833</td>
<td>0.866</td>
<td>0.82</td>
<td>0.68</td>
<td>13.02</td>
<td>93</td>
<td>81.5</td>
<td>8.7</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
<tr>
<td>10/21/10 13:37</td>
<td>0.773</td>
<td>0.876</td>
<td>0.921</td>
<td>0.88</td>
<td>0.723</td>
<td>13.02</td>
<td>93</td>
<td>81.5</td>
<td>8.68</td>
<td>0.059</td>
<td>0.5877646</td>
</tr>
</tbody>
</table>

Figure 18 shows the results from the previous experiment on circular skylights with 10% AFR (Aperture to floor area ratio) in two arrangements: 2x2 and 3x3 array of skylights with equal distance from each other. Figure 8 shows the results from simulation of square skylights with 7% AFR in the same two arrangements.
Different tones of red and blue colors represent various sensors lines across the width of the model, shown in figure 18. The horizontal axis represents the 24 data collection spots along the length of the models. The vertical axis shows illuminance levels in 0.1 Klux.

![Figure 19 Illuminance levels in the simulated models with 5.5% AFR, 54% transmissivity in the middle axis](image)

(A) 2x2 square-localized apertures (skylights)  
(B) 3x3 square-localized apertures (skylights)

The vertical axis shows illuminance levels in lux and vertical axis shows sensors in the space

Figure 20 shows illuminance levels in the previous study in physical models with 10% AFR with two and three linear apertures. Figure 10 shows the results from simulation of two and three linear apertures with 7% AFR.
Figure 20 Illuminance levels in the physical models with 10% AFR and sunshades:

A) 2 linear apertures
B) 3 linear apertures

The vertical axis shows illuminance levels in 0.1 Klux.
4.3.1.6. Conclusions and Discussion

Comparison of the results from the physical experiment and the simulation show general similarities in fluctuations of light levels underneath the apertures. However, there are differences in illuminance levels due to differences between physical and virtual models. Reasons for different illuminances in the physical models compared to the virtual models include:

Differences in transmissivity of the glazing materials: in physical models the apertures were not covered by any glazing material, only narrow sunshades were built to let in all the sunlight from the sky except for the beam light. On the contrary, in simulated models, diffuse materials with 54% light transmissivity were modeled, resulting in lower illuminances inside the spaces.

Differences of AFR in models: in simulation the aperture to floor area ratio was 5.5%, whereas in experiment the AFR was 10%.
Difference of surfaces’ light reflectance: the major difference between physical and simulated models resulted from the bright color on the physical models’ ceiling with 90% reflectance, and floor with 60% reflectance. The simulated models had 80% reflectance from ceiling and 20% reflectance from floor area. Therefore, reflected light particularly from the floor could be a reason for higher illuminances in the physical models.

Difference in height of the models, changed from 10’ in experiment to 9’ in simulation.

Difference in time of data collection: experiment was conducted in a clear sunny day, whereas simulation was run for a sample September 21st day from the weather file.

Difference in locations: Raleigh was the location where the experiment was conducted and Boston was the city selected for simulation.

Difference between computer models and physical models. In computer models, the main daylighting grid was located in a module surrounded by eight similar modules in order to get rid of the effects of the walls. In order to avoid discrepancies between computer simulations and experiment, the physical models should be created with the same condition as the virtual models in daylighting simulations.

In the previous experiment, the sunshades should have been adjusted during data collection for each model. The reason was the fact that some beam light were entering the apertures due to notable changes in sun position during a set of data collection. Having narrow sunshades could have let beam sunlight penetrate inside the models and that could have been a possible reason for high illuminance values gained from the experiment.

One problem in the experimental process that should be solved for future experiments was the timing issue; collecting data for 24 points along the models’ length approximately required 15 minutes; changing the models, taking a photo with the camera extended this time to about 20 minutes, resulting in 4 hours for ten models. Having a row of sensors on the base and measuring illuminance levels for each model at once will solve this problem.

In this section, an experimental process was explained in order to verify the key results derived from a daylighting simulation with Radiance. Some recommendations were made from future experiments by comparing the results of a previous physical study with a comparable simulation for identical models. It is aimed that these recommendations help to achieve an accurate process of data collection in future daylighting experiments. This comparison showed that the results from simulation are
reliable and comparable results could be achieved if the actual and virtual models are made the same. Validity of Radiance simulation program has been proved previously as explained in the literature review (see chapter 2.2), this section proved that the simulation process could be exactly repeated in a physical experiments. Some suggestions and recommendations were made based on the previous experience.

4.3.2. Building Load Calculations with Cooling Load Temperature Difference (CLTD)

The effect of daylighting in a building obviously goes beyond savings for lighting fixtures, extending into the HVAC system. Computer models and simulations can be used to approximate these effects, but providing some independent analytical computations is necessary to confirm the computer model. One method used in this section is the CLTD method created by ASHRAE. First, the CLTD method is discussed then calculations of cooling and heating loads are presented. It is outlined how the presence of daylighting affect the building loads by making comparisons with the base case, where no roof apertures exist. In this section a methodology is provided to confirm the simulated model for one hour (given some design outside temperature, humidity, and solar radiation).

4.3.2.1. Cooling Load Temperature Difference (CLTD) Method

The Energy Balance for calculation of loads for a space is the following:

Energy in - Energy out = Accumulated energy

\[ Q_{\text{loss}} - Q_{\text{gains}} = Q_{\text{loads}} \]

\[ (Q_{\text{walls & windows}} + Q_{\text{roof & floor}} + Q_{\text{ventilation}}) - (Q_{\text{internal}} + Q_{\text{solar}}) = Q_{\text{loads}} \]

The calculation of loads for a space involves calculating a surface-by-surface conductive, convective, and radiative heat balance for each room surface and a convective heat balance for the room air. For a sample wall surface, with heat flux via conduction and convection, the energy balance could be written as the following:

Energy in - Energy out = Accumulated energy

\[ q_{i,t \ \text{conduction}} = q_{i,t \ \text{convection}} \]

By Fourier’s Law, heat conduction through the wall at point x:

\[ q_{x \ \text{conduction}} = -k A \left( \frac{dT}{dx} \right) \]
Convective heat transfer occurs because of temperature differences on both sides of the wall at time t:

\[ q_{x,\text{convection}} = h \ A \ \Delta T \]

\( q_{x,\text{convection}} \) = convection heat flux
\( h \) = heat transfer coefficient
\( A \) = surface area
\( \Delta T \) = temperature difference between surfaces

Therefore, the energy balance at point x becomes:

\[ q_{i,\text{conduction}} = q_{i,\text{convection}} - k \ (\frac{\partial T}{\partial x}) = h \ [T_{x=L, t} - T_{x=0, t}] \]

\( \frac{\partial T}{\partial x} \) = temperature gradient in x distance from the surface
\( T_{x=L, t} \) = temperature at L distance form the surface at time t
\( T_{x=0, t} \) = temperature on interior surface where x=0

For a sample room enclosed by four walls, a ceiling and a floor, the energy exchange at each inside surface at a given time will be changed when considering solar radiation:

\[ q_{i,t} = [h_{c,i} (T_{a,t} - T_{i,t})] + Q_{\text{radiation, net}} \]

\[ q_{i,t} = [h_{c,i} (T_{a,t} - T_{i,t})] + \sum_{j=1}^{m} \ g_{ij} (T_{j,t} - T_{i,t}) \sum_{i=1}^{n} \ g_{ij}(T) \ (t-T_{i,t}) \] \ A_i \]

for \( i=1,2,3,4,5,6 \)

(Reference: Chapter 7, ASHREA 2009, page 220)

\( m \) = number of surfaces in a room
\( q_{i,t} \) = rate of heat conducted into surface i at inside surface at time t
\( A_i \) = area of surface i
\( h_{c,i} \) = convective heat transfer coefficient at interior surface i
\( T_{a,t} \) = inside air temperature at time t
\( T_{i,t} \) = average temperature of interior surface i at time t
\[ q_{i,t} = [h_{c,i}(T_{a,i} - T_{i1}) + \sum g_{ij}(T_{j1} - T_{i1}) \sum_{j=1}^{m} g_{ij}(T_{j}, t - T_{i}, t)] A_{i} + RS_{i,t} + RL_{i,t} + RE_{i,t} \]

for \( i=1,2,3,4,5,6 \)

(Reference: Chapter 7, ASHREA 2009, page 220)

\( RS_{i,t} \) = rate of solar energy coming through windows and absorbed by surface \( i \) at time \( t \)

\( RL_{i,t} \) = rate of heat radiated from lights and absorbed by surface \( i \) at time \( t \)

\( RE_{i,t} \) = rate of heat radiated from equipment and occupants and absorbed by surface \( i \) at time \( t \)

Since these equations are difficult to solve, **Cooling Load Temperature Difference (CLTD)** Method is suggested by ASHRAE in 1985, to simplify the calculation of cooling loads with consideration to thermal mass and solar effects. In CLTD Method, the total cooling load of a room is composed of three parts, accounting for gains through walls, roof, and fenestration.

\[ Q_{\text{total cooling load}} = Q_{\text{walls}} + Q_{\text{roof}} + Q_{\text{fenestration}} \]

To create simplified CLTD Method, hour-by-hour cooling loads from rooms with a number of roof, wall and window construction types were calculated; dividing the cooling load by the \( U \)-values for each roof or wall resulted in acquisition of CLTD factors.

\[ CLTD_{\text{sample}} = \frac{Q_{\text{cooling load}}}{U_{\text{sample}}} \]

\( Q \) = measured cooling load for a unit area of a sample construction type

It is assumed that the heat flow through a similar roof or wall (similar in thermal mass or weight as well as \( U \)-value) can be obtained by multiplying the total CLTDs by the \( U \)-value of another roof or wall. CLTD\(_{\text{base}} \) values are calculated for three types of rooms with heavy, medium and light thermal characteristics. Errors in this method depend on the extent of the differences between the construction in question and the one used for calculating the temperature differences.

CLTD\(_{\text{base}} \) values are provided in tables for simplification of cooling load calculations for various roofs, walls, and fenestration types. CLTD\(_{\text{base}} \) is computed in a room with indoor air temperature of 78 F, outdoor maximum temperature of 95 F, and an outdoor mean temperature of 85 F, with an outdoor
daily ranges of 21 deg F (and a solar radiation variation typical of 40N latitude on July 21). As a result, some tables are provided for correcting the CLTD factor.

For walls and roof, cooling load is calculated from the following equation:

\[ Q_{\text{walls\&roof}} = U \cdot A \cdot CLTD_{\text{correction}} \]

\[ CLTD_{\text{correction}} = [CLTD_{\text{base}} + (LM)] + (78 \cdot T_i) + (T_o - 85) \]

CLTD_{\text{base}}: CLTD values for various roof and wall construction types for different orientations (for walls)

LM: Latitude month correction

Ti: Temperature Inside

To: Average Temperature Outside

Cooling loads from windows and openings are calculated from the following equation:

\[ Q_{\text{fenestration}} = Q_{\text{direct radiation}} + Q_{\text{diffuse radiation}} + Q_{\text{conduction}} \]

\[ Q_{\text{fenestration}} = [A_w \cdot SC \cdot SHGF \cdot CLF] + U \cdot A_w \cdot CLTD_w \]

Where:

A_w: Window area

SC: Shading Coefficient

SHGF: Solar Heat Gain Factor

CLF: Cooling Load Factor

U: Heat Transfer Coefficient

CLTD_w: CLTD values for various types of windows

4.3.2.2. Calculations for the Research Models

This section provides a methodology for conducting a simple hand calculation of heating and cooling loads for one of the models (skylights with 5.5% AFR (Aperture to Floor Area Ratio)) in both Boston and Miami. The purpose is to add validation to the simulation method by making comparisons between independent calculations and simulation. CLTD Method is an analytical way of verifying that the more sophisticated model such as EnergyPlus in this research is reasonable and is capturing the important factors.

Climate Data: Source of climate data used in hand calculations in ASHRAE 2009 handbook-Fundamentals.
Table 30 Boston climate data

<table>
<thead>
<tr>
<th>CLIMATE DATA for Boston, ASHRAE</th>
<th>Cooling</th>
<th>0.4% Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location [City, State]</td>
<td></td>
<td>Boston, MA</td>
</tr>
<tr>
<td>Outside dry bulb Temperature [oF]</td>
<td>90.80</td>
<td></td>
</tr>
<tr>
<td>Humidity ratio [lbs moisture/lb dry air]</td>
<td>0.0136</td>
<td></td>
</tr>
<tr>
<td>Summer occupied setpoint [oF]</td>
<td>76.1</td>
<td></td>
</tr>
<tr>
<td>Summer occupied humidity ratio [lbs moisture/lb dry air]</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Total Solar Radiation - Horizontal [Btu/ft2/day]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Outside temperature in July 9th</td>
<td>87.36</td>
<td></td>
</tr>
</tbody>
</table>

CLIMATE DATA, ASHRAE Heating 99.6% Data

| Outside dry bulb Temperature [oF] | 7.40  |   |
| Humidity ratio [lbs moisture/lb dry air] |   |   |
| Winter occupied setpoint [oF]      | 71.6  |   |
| Winter occupied humidity ratio [lbs moisture/lb dry air] | 0.008 |   |

Table 31 Miami climate data

<table>
<thead>
<tr>
<th>CLIMATE DATA for Miami, ASHRAE</th>
<th>Cooling</th>
<th>0.4% Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location [City, State]</td>
<td></td>
<td>Miami, FL</td>
</tr>
<tr>
<td>Outside dry bulb Temperature [F]</td>
<td>91.80</td>
<td></td>
</tr>
<tr>
<td>Humidity ratio [lbs moisture/lb dry air]</td>
<td>0.0172</td>
<td></td>
</tr>
<tr>
<td>Summer occupied setpoint [F]</td>
<td>76.1</td>
<td></td>
</tr>
<tr>
<td>Summer occupied humidity ratio [lbs moisture/lb dry air]</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Total Solar Radiation - Horizontal [Btu/ft2/day]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Outside temperature in July 29th</td>
<td>87.04</td>
<td></td>
</tr>
</tbody>
</table>

CLIMATE DATA, ASHRAE Heating 99.6% Data

| Outside dry bulb Temperature [F] | 7.40  |   |
| Humidity ratio [lbs moisture/lb dry air] |   |   |
| Winter occupied setpoint [F]      |       |   |
| Winter occupied humidity ratio [lbs moisture/lb dry air] | 0.008 |   |

Peak Cooling Load Calculation:

For cooling load calculations, both base case with no roof apertures and the model with skylights are be examined. The reason is to ensure that the effects of solar radiation through the glazing cooling on cooling load calculations are taken into account.

Base case with no roof apertures: Table 32 shows the peak cooling load calculations for the base case with CLTD method in Boston. These calculations are made with ASHRA 2009, 0.4% cooling climate data as shown in table 32.
To compare hand calculations with simulation, hourly energy analysis results from EnergyPlus are plotted and the 0.4% data were selected. The results show that the total sensible cooling load calculated from the CLTD method is 9,535 [kBtu] and the total sensible cooling load from the simulated model in EnergyPlus is 10410.73 [kBtu].

Table 32 CLTD Method for base case in Boston

<table>
<thead>
<tr>
<th>1. ZONE DATA</th>
<th>British Units</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>zone name</td>
<td>[name]</td>
<td>Office</td>
</tr>
<tr>
<td>zone area</td>
<td>[ft²]</td>
<td>900 [m²]</td>
</tr>
</tbody>
</table>

2. INTERNAL GAINS

PEOPLE

<table>
<thead>
<tr>
<th></th>
<th>[Btu/h]</th>
<th>[W]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of people</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>sensible heat gain per person</td>
<td>245</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>latent heat gain per person</td>
<td>155</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>total heat gain per person</td>
<td>400</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>total people heat gain - sensible</td>
<td>980</td>
<td>287</td>
<td></td>
</tr>
<tr>
<td>total people heat gain - latent</td>
<td>620</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>total people heat gain</td>
<td>1600</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. LIGHTS

<table>
<thead>
<tr>
<th></th>
<th>[Btu/h/ft²]</th>
<th>[W/ft²]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>lighting power density</td>
<td>3.07</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Total Light Levels</td>
<td>810</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent of LPD use at time</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>total lights heat gain</td>
<td>2762.10</td>
<td>810</td>
<td></td>
</tr>
</tbody>
</table>

4. EQUIPMENT

<table>
<thead>
<tr>
<th></th>
<th>[Btu/h]</th>
<th>[W]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of computers &amp; monitors</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>computer &amp; monitor heat gain</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Printers, scanners, and copiers heat gain</td>
<td>86</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>total equipment heat gain</td>
<td>3021</td>
<td>886</td>
<td></td>
</tr>
</tbody>
</table>

3. ENVELOPE

OPAQUE ROOF

<table>
<thead>
<tr>
<th></th>
<th>[ft²]</th>
<th>[m²]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>900</td>
<td>83.64</td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>0.033</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>CLTD_base (without suspended ceiling, 4&quot; wood with 2&quot; insulation)</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM (latitude 42, horizontal surface, July)</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLTD_correction</td>
<td>49.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside temperature</td>
<td>76.1</td>
<td>24.50</td>
<td></td>
</tr>
<tr>
<td>Average outside temperature</td>
<td>87.36</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>AT CLTD</td>
<td>4.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opaque roof conductive heat gain</td>
<td>1478</td>
<td>433</td>
<td></td>
</tr>
</tbody>
</table>

ROOF Horizontal Glazing

<table>
<thead>
<tr>
<th></th>
<th>[ft²]</th>
<th>[m²]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>0</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>solar heat gain coefficient</td>
<td>0</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Shading Coefficient (SC)</td>
<td>0</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Solar Heat Gain Factor (SHGF)

Cooling Load Factor (CLF)

CLTD base horizonal window

<table>
<thead>
<tr>
<th></th>
<th>[Btu/h]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>window solar radiation heat gain</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>window conductive heat gain</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

4. AIRFLOW
<table>
<thead>
<tr>
<th>VENTILATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of people</td>
</tr>
<tr>
<td>ventilation requirements</td>
</tr>
<tr>
<td>ventilation requirements</td>
</tr>
<tr>
<td>total ventilation needed</td>
</tr>
<tr>
<td>ventilation needed</td>
</tr>
<tr>
<td>inside temperature</td>
</tr>
<tr>
<td>outside temperature</td>
</tr>
<tr>
<td>ΔT</td>
</tr>
<tr>
<td>inside humidity ratio</td>
</tr>
<tr>
<td>outside humidity ratio</td>
</tr>
<tr>
<td>AW</td>
</tr>
<tr>
<td>total ventilation heat gain - sensible</td>
</tr>
<tr>
<td>total ventilation heat gain - latent</td>
</tr>
<tr>
<td>Total ventilation heat gain</td>
</tr>
</tbody>
</table>

5. COOLING LOAD TOTALS, Base case, Boston

| People | [Btu/h] | 1,600 | [w] | 469 |
| Lights | [Btu/h] | 2,762 | [w] | 810 |
| Equipment | [Btu/h] | 3,021 | [w] | 886 |
| Envelope - conduction roof | [Btu/h] | 1,478 | [w] | 433 |
| Ventilation | [Btu/h] | 1,913 | [w] | 561 |
| Total cooling load | [Btu/h] | 10,774 | [w] | 3160 |
| Total cooling load/unit area | [Btu/h-ft2] | 12.0 | [w]/m2 | 38 |
| Total sensible cooling load | [Btu/h] | 9535 | [w] | 2796.14 |
| Total latent cooling load | [Btu/h] | 1240 | |
| Sensible Heating Factor | | | 0.88 |

Comparison of the results from the CLTD method and the EneyPlus simulation shows a trivial difference between the two methods for the base case in Miami. The total sensible cooling loads are calculated as 9628 [kBtu] in the CLTD method and 9342 [kBtu] from EnergyPlus.

Table 33 Summarized CLTD Method for base case in Miami

| people | [Btu/h] | 1,600 | [w] | 469 |
| lights | [Btu/h] | 2,762 | [w] | 810 |
| equipment | [Btu/h] | 3,021 | [w] | 886 |
| envelope - conduction roof | [Btu/h] | 1,483 | [w] | 435 |
| ventilation | [Btu/h] | 3,395 | [w] | 996 |
| total cooling load | [Btu/h] | 12,262 | [w] | 3596 |
| total cooling load/unit area | [Btu/h-ft2] | 13.6 | [w]/m2 | 43 |
| Total sensible cooling load | [Btu/h] | 9628 | [w] | 2824 |
| Total latent cooling load | [Btu/h] | 2633 | [w] | 772 |
| Sensible Heating Factor | | | 0.79 |
Skylights with 5.5% AFR (Aperture to Floor Area Ratio): The total sensible cooling loads are calculated as 12126 [kBtu] from CLTD method hand calculations and 12510 [kBtu] from simulation in EnergyPlus. In Miami this value is calculated as 12671 [kBtu] in the hand calculations and 12956 [kBtu] in the EnergyPlus hourly simulations. Table 34 and 35 show the CLTD method results for the models with 5.5% SFR in Boston and Miami.

Table 34. CLTD Method for skylights with 5.5% AFR (Aperture to Floor Area Ratio) in Boston

<table>
<thead>
<tr>
<th>1. ZONE DATA</th>
<th>British Units</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. INTERNAL GAINS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(similar to the base case)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-1. OPAQUE ROOF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>area [ft²]</td>
<td>836</td>
<td>77.70</td>
</tr>
<tr>
<td>U-value [Btu/ft²°F]</td>
<td>0.033</td>
<td>0.19</td>
</tr>
<tr>
<td>CLTD_base (without suspended ceiling, 4” wood with 2” insulation)</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>LM (latitude 42, horizontal surface, July)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>CLTD_correction</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>inside temperature [°F]</td>
<td>76.1</td>
<td>24.50</td>
</tr>
<tr>
<td>Average outside temperature [°F]</td>
<td>87.36</td>
<td>0.00</td>
</tr>
<tr>
<td>NT CLTD [°F]</td>
<td>4.26</td>
<td></td>
</tr>
<tr>
<td>Opaque roof conductive heat gain [Btu/h]</td>
<td>1373</td>
<td>403</td>
</tr>
</tbody>
</table>

3-2. ROOF Horizontal Glazing

| area [ft²]             | 64            | 5.95    |
| U-value [Btu/ft²°F]    | 0.64          | 3.64    |
| solar heat gain coefficient [%] | 0.32         | 0.32    |
| Shading Coefficient (SC) [%] | 0.42         |         |
| Solar Heat Gain Factor (SHGF) | 259          |         |
| Coolign Load Factor (CLF) | 0.71          |         |
| CLTD_base horizontal window | 14.00        |         |
| window solar radiation heat gain [Btu/h] | 4884        | 1432.29 |
| window conductive heat gain [Btu/h] | 574          | 168.33  |
| Total [Btu/h]          | 5458          | 1600.63 |

4. AIRFLOW (similar to the base case)

5. COOLING LOAD TOTALS for Skylights in Boston

| people [Btu/h] | 1,600 | [w] | 469 |
| lights [Btu/h] | 0     | [w] | 0   |
| equipment [Btu/h] | 3,021 | [w] | 886 |
| ventilation [Btu/h] | 1,913 | [w] | 561 |
| total cooling load [Btu/h] | 13,365 | [w] | 3919 |
| total cooling load/unit area [Btu/h/ft²] | 14.9 | [w]/m² | 47 |
| Total sensible cooling load [Btu/h] | 12126 |         |
| Total latent cooling load [Btu/h] | 1240 |         |
| Sensible Heating Factor | 0.91 |         |
Peak Heating Load Calculation

Peak Heating Load Calculation was conducted for a Winter Design Day based on ASHRAE 99.6\% Data. Climate data for Boston and Miami are illustrated in tables 36. Peak heating load calculations for skylights with 5.5\% AFR in Boston (table 36) is 10.70 [kBtuh/ft²].

For comparing the hand calculations with simulation, the hourly results from EnergyPlus simulation were sorted and 99.6\% climate data were selected. Simulating the same models in the same location in EnergyPlus showed 11.32 [kBtuh/ft²] heating loads.

Table 36 Peak Heating load calculations for skylights with 5.5\% AFR in Boston

<table>
<thead>
<tr>
<th>1. Internal Load</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Opaque Roof</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>836 [ft²]</td>
</tr>
<tr>
<td>U-value</td>
<td>0.033</td>
</tr>
<tr>
<td>Conductive Heat Loss through Opaque Roof</td>
<td>1771.15</td>
</tr>
<tr>
<td>3. Skylights Glazing</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>64.00</td>
</tr>
<tr>
<td>U-value</td>
<td>0.64</td>
</tr>
<tr>
<td>Conductive Heat Loss through Glazing part of Roof</td>
<td>2629.63</td>
</tr>
<tr>
<td>4. Ventilation</td>
<td></td>
</tr>
<tr>
<td>Required Air Volume</td>
<td>74.00 [cfm]</td>
</tr>
<tr>
<td>Ventilation Sensible Heat Loss</td>
<td>5225.88</td>
</tr>
<tr>
<td>TOTAL HEATING LOADS</td>
<td>9626.66 [kBtu]</td>
</tr>
<tr>
<td>TOTAL HEATING LOADS per Sqft</td>
<td>10.70 [kBtuh/ft²]</td>
</tr>
</tbody>
</table>
Peak heating load calculation in models with 5.5% AFR skylights in Miami (table 37) shows 3.98 [kBtuh/ft²]. This value in EnergyPlus simulation is calculated as 4.2 [kBtuh/ft²].

Table 37 Peak Heating load calculations for skylights with 5.5% AFR in Miami

<table>
<thead>
<tr>
<th>1. Internal Load</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Opaque Roof</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>836 [ft²]</td>
</tr>
<tr>
<td>U-value</td>
<td>0.033</td>
</tr>
<tr>
<td>Conductive Heat Loss through Opaque Roof</td>
<td>659.35</td>
</tr>
<tr>
<td>3. Skylights Glazing</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>64.00</td>
</tr>
<tr>
<td>U-value</td>
<td>0.64</td>
</tr>
<tr>
<td>Conductive Heat Loss through Glazing part of Roof</td>
<td>978.94</td>
</tr>
<tr>
<td>4. Ventilation</td>
<td></td>
</tr>
<tr>
<td>Required Air Volume</td>
<td>74.00 [cfm]</td>
</tr>
<tr>
<td>Ventilation Sensible Heat Loss</td>
<td>1945.46</td>
</tr>
<tr>
<td>TOTAL HEATING LOADS</td>
<td>3583.76 [kBtu]</td>
</tr>
<tr>
<td>TOTAL HEATING LOADS per Sqft</td>
<td>3.98 [kBtuh/ft²]</td>
</tr>
</tbody>
</table>

4.3.3. Conclusions and Discussion

All the factors interact on a time dependent basis to determine a cooling or heating load. The addition of solar radiation to the space provides benefits because electric lighting is reduced, but it can add to the cooling load in the summer such that the net benefit is negated. CLTD method is selected as a simple hand calculation to validate results from EnergyPlus simulations. Results from hand calculations and simulation showed 20%-30% difference. The main reason for the difference between two methods is due to the different existed in the climate data used in hand calculations and simulation. For hand calculations, climate data from ASHRAE 2009 was used but for EnergyPlus, the hourly climate data provided by the US Department of Energy (US DOE) is used. The other difference is attributable to the steady-state condition that is assumed in hand calculations versus the dynamic condition in simulation tools. Nevertheless, this section showed that the hourly results from simulation is comparable to the hand calculations adding validity to the energy simulation process.
CHAPTER 5: RESEARCH FINDINGS

5.1. LIGHTING ASSESSMENT

This section discusses the independent variables, dependent variables, and building parameters of the study.

5.1.1. Point-in-Time Daylighting Simulation Outputs

5.1.1.1. Horizontal Apertures

Three configurations of skylights were simulated in Boston and Miami via Radiance with the use of Diva-for-Rhino plug in. The models include:

1. Skylights with no integration of the ductwork into the structural volume and with squared-off light wells

2. Skylights with the ductwork integrated into the structural volume and with a beveled light well

3. Skylights with the ductwork integrated into the structural volume, and extended-splay light wells (no horizontal ceiling)

(See chapter 4.2.2.1 and figures 2A, 2B, and 2C)

Figure 2 and 3 show Illuminance distribution in modules with 5.5% AFR square apertures received at 25 sensors located on a diagonal axis at task surface (see figure 1 and chapter 4.1.3 for more information). The following charts show the results of the simulation with the aforementioned settings and Radiance parameters of ab 8, ad 3600, as 900, ar 600, and aa 0.05. The horizontal axis in the charts represents the numbers of the sensors and vertical axis depicts illuminances in lux.
Single-point-in-time illuminance simulations reveal that average illuminance levels are higher in horizontal apertures located in Miami than the ones located in Boston. Average illuminance in the diagonal axis of task surface in a space roofed with square apertures with 5.5% AFR in Boston is about 80% of the average illuminance of the same room in Miami. This fact is due to higher solar altitude angles at equinox noon in Miami (90°) compared to Boston (71°).

In addition to explore the effect of building’s location on illuminance levels, the target was to explore the effect that depth and shape of light well has on illuminance levels received in the space. The depth of light well is 5’7” and it is squared-off in the first case. Depth of light well is reduced by 2’ when the ductwork is replaced to the space allocated for structure. Depth of light well reaches 3’7” and it is splayed with 45° to admit more daylight into the space. In the third case, light wells sloped with 60° angle and extended to reach a triangular cross section, which is apportioned to ductwork and located between two skylights.
Not surprisingly, the first case configuration with the deep, squared-off light well is the poorest performer both in terms of the low amount of light reaching the task surface and in terms of the extreme variations in illuminance levels. The low quantity of light is attributable to the high numbers
of bounces and the high absorption of light on the surfaces of the light well. The high variations in the illuminance on the task surface are attributable to the light well selecting against low-angle light and easily passing the light rays moving nearly vertically down through the light well. This tends to create high illuminance directly below the skylights and relative darkness between the skylights.

Average illuminance in skylights with sloped and integrated light wells is 1.8 times the average illuminance in un-integrated and squared off light wells (figure 4).

Shallower light wells with slopes results in reception of higher illuminance levels in a space; the reason lies in the fact that more solar rays enter a space without hitting an obstruction. With the use of shallower and sloped light wells, less light fluctuations occur in the space (figure 5). High variations in the daylight illuminance level create the following problems:

Electric lighting systems with control algorithms that control uniformly across the space must control based on the lowest daylight illuminance in the space. Otherwise, the occupants at those locations will be deprived of the appropriate illuminance. In that case, parts of the space with relatively high illuminance may have an excess of light for certain tasks, such as working on computer screens. The excess daylight in those locations will also be a source of thermal overload that will drive up the cooling costs for the building.

Electric lighting systems with control algorithms that tailor the distribution of illuminance from the electrical sources to compensate for the wide variations in daylight illuminance will be complex and expensive and will never work perfectly effectively in filling in the “holes” in the daylighting, without expending additional energy in the form of excess electric illumination in some places. For the purposes of this study, all of the electric lights were assumed to be controlled based on the simple algorithm that the electric lighting illuminance everywhere in the space is to be elevated by whatever amount is needed to compensate for the daylighting deficiency at the location in the space where the daylighting illuminance is a lowest. For all the skylight configurations, the minimum daylight illuminance in the space occurs at sensor 13 (between the skylights).

The average illuminance across the space for skylights with extended splayed light wells is 1.03 times higher than the average illuminance across the space for the integrated and beveled configuration (figure 4), which is not very dramatic. However, the extended splay configuration is expected to be visually more pleasing, since there will be no dark, horizontal areas of ceiling to create visual contrast.
Figure 5 shows illuminance variations that occur at noon September 21 in various configurations of skylights. Skylights with ductwork integrated with the structure and beveled light wells outperform the conventional, squared-off skylights considering that the maximum to minimum illuminance ratio in squared off light wells is 6 times that ratio for integrated and beveled light wells. The simulations indicate that the variations in illuminance for the extended splay configuration are slightly greater than for the integrated, beveled configuration.

![Figure 4 Average luminance in skylights with different light-well shapes in Boston and Miami (skylights have 5.5% AFR, point-in-time results for Sep 21, 12 pm)](image)

![Figure 5 Illuminance variations in skylights with different light-well shapes in Boston and Miami (for skylights having 5.5% AFR, point-in-time results for Sep 21, 12 pm)](image)

A major purpose of this study is to find the optimum area of skylight apertures, where the advantages of reduced electric lighting due to daylighting overcome the thermal disadvantages of increased conductive heat loss and increased solar heat gain through the glazing material. The square apertures
were modeled with: 2%, 3.5%, and 5.5% AFR (AFR=Aperture-Area-to-Floor-Area-Ratio) and linear apertures were modeled with: 5.5%, 7.5%, and 10% AFR.

Figures 6 and 7 show daylight illuminance distribution at 12 pm September 21 in Boston and Miami for square and linear apertures with different AFRs. In the module with square apertures, 25 sensors are located on the diagonal axis at task level, whereas, in the module with linear apertures, 25 sensors are located in the middle axis in North-South direction (Figure 1). This arrangement is selected to capture maximum and minimum illuminances for both square and linear skylight configurations. Both the square and linear skylights are designed with integrated systems and bevelled light-wells (sections of models are shown in chapter 4 in figure 2B).

The results show that the average daylight illuminance increases as the AFR increases. However, the increase in average illuminance is not directly proportional to the AFR, because of light-well effects. All of the apertures within a given configuration have the same depth and shape of light well. Within that configuration, smaller apertures have light wells with narrower, more “tunnel-like” proportions, resulting in more light absorption on the light-well walls, which reduces the daylight that reaches the work plane as illuminance (table 1).

Table 1 Average daylight illuminance in square and linear skylights with various aperture sizes

<table>
<thead>
<tr>
<th>AVERAGE DAYLIGHT ILLUMINANCE (LUX)</th>
<th>Linear Apertures</th>
<th>Square Apertures</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFR</td>
<td>3.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Boston</td>
<td>340</td>
<td>654</td>
</tr>
<tr>
<td>Miami</td>
<td>346</td>
<td>821</td>
</tr>
</tbody>
</table>

Figure 6 Square skylights illuminance distribution on diagonal axis at task level in Boston and Miami
In addition, results show that the average daylight illuminance in linear apertures is lower than the square apertures with the same AFR. As an instance, linear apertures with 5.5% AFR have 654 lux average daylight illuminance, which is comparable to the average illuminance received in the square apertures with 3.5% AFR; square apertures with 5.5% AFR receive much higher average daylight illuminance about 1084 lux inside the space (table 1).

Linear apertures with 3.5% AFR were eliminated for the next step of the study because of having low daylighting performance as a result of their narrow light-wells.

5.1.1.2. Vertical Apertures

Single and double roof monitors were simulated with Radiance in Diva-for-Rhino for Boston and Miami. The following figures show the results of simulation at 12 pm September 21 with sunny sky condition with ab 8, ad 5184, as 1296, ar 1200, and aa 0.03 Radiance parameters. Building parameters and model sections are shown in chapter 4.2.2.2 in figures 3A, B, and C. The following figures show Illuminance received at the middle axis, which is located in north-south direction (figure 9 and 10); the horizontal axis shows the number of sensors and vertical axis depicts illuminances in lux.

In addition to explore the effect of building’s location on illuminance levels, the target was to compare single monitors and double monitors, which differ in spacing between vertical apertures. In addition, it was aimed to explore the effect that depth of light well has on illuminance levels received in the space. The charts compare the case that have 30’-horizontal run and the case that have 60’-horizontal run in single and double monitors, which differ in their depth of light well. Roof monitors that extend for 60’ have 1’ deeper light well that those which extend for 30’. Light wells are 2’ for
configurations with 30°-horizontal run and they are 3’ for configurations with 60°-horizontal run (for more information see chapter 4.2.2.2).

Figure 8 Location of sensors at
(A) Single roof monitors    (B) double roof monitors

Figure 9 Illuminance distribution [lux] in single roof monitors with 20% AFR in Boston and Miami
The simulations indicate that the average illuminance in the middle axis of the space in Miami is about 85% of the average illuminance of the same space in Boston in both single and double roof monitors (figures 9 and 10). This is due to higher incidence of solar radiation on vertical surfaces.
when the altitude angles are lower; the altitude angle at equinox noon is 47° in Boston and 65° in Miami.

Figure 9 shows single-moment-in-time illuminance simulations for 20% AFR monitors in Boston and Miami. Two light-well depths were simulated for Boston: squared-off light-wells with 2’ vertical dimension and squared-off light-wells with 3’ vertical dimension. The single roof monitor with the 2-ft-light-well has 1.02 times the average illuminance of 3-ft-light-well (figure 11). In other words, for single roof monitors, the effect of depth of the light well on illumination performance is very small for this range of variation in light-well depth simulated. The difference in depth of light well creates a significant impact on illuminance in double monitors compared to single monitors. Figure 10 (A) shows illuminance distribution in 20% AFR- double monitors with different light-well depths in Boston. In double monitors, the width of the light well has been approximately halved, compared to single monitors. The narrower light well is more “tunnel-like” and therefore absorbs more light, preventing that light from reaching the work plane. For this narrower light well, variations in the depth of the light well prove to be more sensitive than the same variations in depth applied to single monitors. In fact, going from a 3’-deep light well to a 2’-deep light well in the double monitor configuration increases the average illuminance on the work plane by a factor of 1.24 (figure 11).

Comparing single and double monitors, single monitors have twice as much variation in the illuminance across the space as double monitors (figure 12). Despite higher illuminance variation, single monitors do not have higher average illuminance compared to double roof monitors (figure 11). This is due to having more extreme illuminances in the minimum and maximum points: the maximum illuminance in single monitors is about 1000 lux higher, and the minimum illuminance is 700 lux lower than their similar points in double monitors. However, the average illuminance in single monitors is only 109 lux higher than the average illuminance in double monitors, where as it is important to remember that this comparison is made based on simulations at sunny equinox day in Boston, when both single and double monitors were modeled with similar light-wells with 2’ vertical dimension.

In conclusion, double monitors perform better than single monitors considering lower illuminance variation and higher illuminance at points with lowest daylight illuminance. Low quality of daylighting in single monitors is attributable to high variations, which are undesirable due to the reasons mentioned in the section 5.1.1.1 for skylights.
Regarding the squared-off double monitors and the double monitors with minimum light well, it should be mentioned that the average illuminance is slightly higher in the case with minimum light wells. The average illuminance is 1.05 times the average illuminance in double monitors with low-depth squared-off light-wells (figures 10A and B). The difference between low-depth squared-off light wells and minimum light wells is mostly in the architectural characteristics in these two spaces, but the minimum level of illuminance is the same in these two cases. In addition, the roof monitors with minimum light wells could be expanded for 60’ horizontal run, which means creating a space without interruption of columns. On the other hand, squared-off double roof monitors could be expanded only for 30’ to keep their light-wells within 2’ vertical dimension. Besides appreciation of the architectural features that this roofing configuration creates, the annual eclectic energy use is similar to the spaces with double monitors squared-off light wells due to similar lighting schedules created in response to the photosensor, which is located in the spot with minimum illuminance.

Figure 11 Average illuminance in single and double roof monitors with 20% AFR in Boston and Miami
The purpose of this study is to find the optimum aperture area for roof monitors, where the advantages of reduced electric lighting due to daylighting overcome the thermal disadvantages of increased conductive heat loss and increased solar heat gain through the glazing material. As a result, apertures sizes varied from 15%, 20%, and 25% AFR (Aperture to Floor area Ratio). Illuminance distributions at equinox noon are plotted for AFR variations of single and double monitors at 25 sensors located on the middle north-south axis at task level for Boston and Miami and both single and double roof monitors are designed with 2’ squared-off light-wells (Figures 13 and 14). Table 2 summarized the average illuminance levels in all cases.
Figure 13 Illuminance distributions for single monitors with various AFRs in Boston and Miami

Figure 14 Illuminance distributions for double monitors with various AFRs in Boston and Miami
Table 2 Average daylight illuminance in square and linear skylights with various aperture sizes

<table>
<thead>
<tr>
<th>AVERAGE DAYLIGHT ILLUMINANCE (LUX)</th>
<th>Single Monitors</th>
<th>Double Monitors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AFR</strong></td>
<td><strong>Boston</strong></td>
<td><strong>Miami</strong></td>
</tr>
<tr>
<td>15%</td>
<td>1981</td>
<td>1737</td>
</tr>
<tr>
<td>20%</td>
<td>2593</td>
<td>2217</td>
</tr>
<tr>
<td>25%</td>
<td>3106</td>
<td>2693</td>
</tr>
<tr>
<td><strong>AFR</strong></td>
<td><strong>Boston</strong></td>
<td><strong>Miami</strong></td>
</tr>
<tr>
<td>15%</td>
<td>2035</td>
<td>1741</td>
</tr>
<tr>
<td>20%</td>
<td>2484</td>
<td>2076</td>
</tr>
<tr>
<td>25%</td>
<td>3006</td>
<td>2582</td>
</tr>
</tbody>
</table>

**5.1.2. Electric Lighting Energy Use**

**5.1.2.1. Horizontal Apertures**

Figure 15 compares daily average electric lighting energy use in each month of a year in the base case and two square skylights with different light-well shapes in Boston. The base case, which is a model with an opaque roof, only relied on electric lighting and used 6.49 [kWh] daily average electric lighting energy. The first case is the conventional skylights with squared-off light-wells with 5’7” vertical dimension; the second case is designed for higher daylighting performance with light-wells bevelled at 45° and less vertical dimension (3’7”) due to integration of ductwork into the structure (refer to building parameters in section 4.1. for more information). Both daylit cases have square skylights with 5.5% AFR. Results in figure 15 show lower reliance on electricity for lighting purposes in square skylights with bevelled skylights and integrated systems than the conventionally constructed skylights. Significant savings on electric lighting is revealed in the skylights with integrated and bevelled light-wells in figure 15. Because of the apparent daylighting benefits of these configurations of skylights, this system was chosen as the focus for whole-building energy assessment in the next step of the study.

![Figure 15 Daily average lighting electricity use [kWh] in square skylights with 5.5% AFR in Boston](image)
Figures 16 and 17 show daily average lighting electricity use for square and linear skylights in Boston and Miami in each month, in units of kWh. The base case is shown to compare spaces with horizontal apertures to the same space with no apertures on the roof. For small AFRs (0 to 2%), the electric consumption goes down rapidly with each additional increment of aperture area. This rapid decrease primarily reflects the influence of beam sunlight, which is intense enough to displace substantial amounts of the electric light, even when the collecting aperture is quite small. At larger AFRs (above 2%), the lighting electricity consumption goes down less rapidly, indicating primarily the effect of diffuse skylight during those hours when beam sunlight is not available or is only weakly incident on the collection glazing.

The reductions in lighting electricity were greater in Miami than Boston, because the lower latitude of Miami results in more availability of sunlight, particularly during the winter months when short days and cloudy conditions seriously limit the effectiveness of daylighting in Boston. The differences in the lighting electricity consumption curves at small apertures are primarily a result of differences in availability of beam sunlight. At small apertures (2% AFR), the lighting electricity consumption for Miami is substantially lower than for Boston. For larger apertures, diffuse skylight becomes more significant, and the major differences in the lighting electricity consumption curves result from differences in the number of hours of daylight.

![Figure 16 Daily average lighting electricity consumption for skylights with various AFRs per month [kWh] in Boston](image)
Figure 17 Daily average lighting electric consumption of skylights with various AFRs per month [kWh] in Miami

5.1.2.2. Vertical Apertures

Figures 18 and 19 show daily average lighting electricity use of single roof monitors in Boston and Miami, as it varies by month. The base case, which is modeled with an opaque roof, has 6.49 [kwh] average daily use of lighting electricity. In these figures, the base case lighting electricity consumption has not been plotted because it would drastically stretch out the graph and make it difficult to see other variations of interest. The lighting electricity consumption goes below 1.0 kWh usage for every roof monitor configuration. This rapid decrease primarily reflects the influence of beam sunlight, which is intense enough to displace substantial amounts of the electric light.
Although Boston had higher average illumination at equinox noon than Miami (figure 9), electric lighting use in Boston is higher in wintertime due to low solar incidence on south-facing vertical surfaces (figures 20A and B). In Boston, solar rays have very low altitude angles during wintertime, there are less sunshine hours per day, and a higher cloud cover reduces the chance of solar incidence on external surfaces. As a result, roof monitors perform better in Miami in the heating season in terms of daylighting performance.
Figures 18 and 19 show that with roof monitors, enough daylight is available for most of the months. Vertical monitors that face south and north cause effective collection for most hours of a day. Furthermore, vertical glazing collects effectively during summer and even during winter when solar altitude angles are lower. The largest difference between variations of AFR occurs in November, December, and January. Particularly, Boston requires more electric lighting than Miami in these months due to lower sun angles and fewer sunshine hours that reduce available outside illumination.

The curves in figures 18 and 19 are drawn based on occupancy schedule from 9am until 5pm on weekdays. Longer hours of building operation will increase the electric load because there is little or no daylight available in early and late hours of a day.

*Figures 20 (A) Hourly Surface External Solar Incident in Boston and Miami for*
* A) South-Facing Surfaces [Btu/sqft]*
* B) North-Facing Surfaces [Btu/sqft]*
5.1.3. Glare Analysis
5.1.3.1. Horizontal Apertures

Glare analysis with Evalglare was conducted for square skylights with 5.5% AFR with diffuse glazing material with 55% visible transmissivity (Vt) in Boston. Figure 21 shows that skylights with un-integrated and squared-off light-wells generate Daylight Glare Probability (DGP) of 37% at noon June 21. That level of DGP falls in perceptible range of glare for occupants as the results from an experiment, in which human subjects responses were associated with DGP (Reinhart and Wienold, 2010). Annual glare analysis in figure 22 shows that perceptible glare only occurs at noon during the summer; intolerable glare occurs only for a few days in summer.

Figure 21 Glare in skylights with un-integrated systems and squared-off light-wells with 5.5% AFR at noon June 21, Boston
In addition, square skylights with integrated systems and beveled light-wells were examined for glare analysis. Models have the same properties as the previous test with 5.5% AFR, diffuse glazing material with 55% visible transmissivity. Figure 23 shows that skylights with integrated and beveled light-wells generate Daylight Glare Probability (DGP) of 39% at noon June 21. That level of DGP is higher than the previous skylights with squared-off light-wells but still falls in perceptible range of glare for occupants (Reinhart and Wienold, 2010). Annual glare analysis in figure 24 shows that intolerable glare occurs for more days than the skylights with squared-off light-wells during the summer.
Conclusions: The benefits of skylights with beveled light-well are significantly more than the skylights with squared-off light-wells. Therefore, the level of light transmissivity was reduced in skylights with beveled light wells from 55% to 42% in order to reduce glare probability in those spaces.
5.1.3.2. Vertical Apertures

Glare analysis with Evalglare was conducted for single roof monitors with 25% AFR in Boston. DGP calculation is based on a camera facing the south-facing aperture, which has diffusive glazing material with 52% visible transmissivity (Vt) (for more information about building parameters see section 4.2.2.2). Figure 25 shows that roof monitors facing south generate Daylight Glare Probability (DGP) of 49% at noon September 21. That level of DGP falls in intolerable range of glare for occupants (Reinhart and Wienold, 2010). Annual glare analysis in figure 26 shows that intolerable glare occurs mostly in times other than summer when more solar incidence occurs on vertical apertures due to lower altitude angles. In summer, overhangs are successful in rejecting beam sunlight from the south apertures. Although diffusive glazing is selected for balancing sunlight, glare creates visual discomfort in spaces with single roof monitors. Two design solutions are made to solve the glare problem in such spaces.

Figure 25 Glare in single roof monitors with 25% AFR at noon September 21, Boston
Roof Monitors with Baffles: Baffles are typical light distributing devices used in spaces with roof monitors. One of the examples of baffles could be seen in the Mount Air Library studied in case studies in section 2.1.2. Baffles with 90% reflectance were modeled in single roof monitors with 25% AFR. Simulations were conducted with the same settings for the previous glare analysis in single roof monitors with diffuse glazing. Figure 27 shows that DGP reduced to 33% and reaches imperceptible range of glare at noon September 21. Baffles were successful in lowering the 49% DGP to a tolerable range of glare.

Roof Monitors with Banners: banners are hanging pieces of cloths that are located in the middle of each roof monitor to equalize daylight received from both south and north. Each banner is moved in vertical direction for 3 to 4 times a year to reject direct beam light. Banners were modeled as white fabrics with 50% transmittance, 50% reflectance (more information about Radiance parameters for the material is provided in chapter 4). Figure 28 shows that DGP reduced to 32% and reaches imperceptible range of glare at noon September 21 with the use of banners.
Figure 27 Glare in single roof monitors with 25% AFR and baffles at noon September 21, Boston

Figure 28 Glare in single roof monitors with 25% AFR and banners at noon September 21, Boston
Impact of light distributing devices on illuminance levels: Figure 29 shows how illuminance levels are changed when baffles and banners are utilized in the space. Baffles create a valley in illuminance distribution curve due to numerous reflections from the surface of each baffle. Banners reduce illuminances on the north side because of intercepting south beam sunlight. In addition to reducing average illuminance on the work plane making the illuminance less uniform, banners will also tend to be more expensive than banners or diffusing glazing.

5.2.WHOLE-BUILDING ENERGY ASSESSMENT

5.2.1. Thermal Comfort

Due to distinct climatic condition in different cities, levels of energy use are expected to differ when the location of models is changed. Figure 30 compares monthly average outdoor dry bulb temperature of Boston and Miami; it also depicts the targeted setpoint temperature, changing from 71.6°F (22°C) in heating season to 76.1°F in cooling season (24.5°C) in occupied hours in thermal zones.

Figure 29 Illuminance distribution in single monitor with 25% AFR, in Boston in Sept 21, 12pm on Middle North-South Axis in the space, 25 sensors are located at task surface.
5.2.1.1. Horizontal Apertures

Hourly operative temperature and relative humidity at occupied hours of a year are acquired from EnergyPlus and are plotted in a psychrometric chart. The purpose is to ensure that thermal comfort is provided in all the occupied hours of a year. The box printed in solid black, represents thermal comfort based on ASHRAE 55-2010 Standard. Figure 31A shows the results from simulating 5.5% SFR skylights with dimming electric control system in Boston and figure 31 B shows the results from the same roofing configuration in Miami. It is understood that thermal comfort is provided with the HVAC system designed for the spaces in most of the occupied hours.
Figure 31: Annual hourly operative temperatures and relative humidity in the thermal zone designed with skylights in

A) Boston

B) Miami
5.2.1.2. Vertical Apertures

Hourly operative temperature and relative humidity at occupied hours of a year were acquired from EnergyPlus and are plotted in a psychrometric chart for spaces roofed with monitors. Figure 32 A shows the results from simulating 20% AFR single roof monitors with dimming electric control system in Boston and figure 32 B shows the results from the same roofing configuration in Miami. It is understood that thermal comfort is provided with the HVAC system designed for the spaces in most of the occupied hours. Data points, which cast out of the box in psychrometric chart, are associated with the extreme heating/cooling conditions.

![Figure 32](image)

Figure 32 (A) Annual hourly operative temperatures and relative humidity in the thermal zone designed with a single roof monitor in Boston
5.2.2. Heating and Cooling Energy Consumption

Figure 33 shows the monthly internal heat gain in the base case with 30’x30’ dimension generated by electric equipment, people, and lights. This figure shows that the rate of internal gains is not constant in all months due to the different numbers of weekends in each month when the internal heat generation reaches zero.
4.3.2.1. *Horizontal Apertures*

*Square Apertures:* In Figures 34 and 35, the daily average heating coil gas consumption (by month) is plotted for various square horizontal roof aperture areas, for both Boston and Miami. For small aperture areas, heating fuel consumption increases with increasing aperture area, resulting primarily from increased conductive losses associated with adding glazing to the roof and the replacement of electric light with sunlight of lower heat content. As the area of apertures increases, heating fuel consumption increases with a lower rate. The reason is that solar gains compensate the combined effect of reduced heat from the electric lights and increased conductive losses associated with increased glazing area.

In Boston, heating fuel consumption (figure 34) is more sensitive than cooling coil consumption (figure 35) to variations in the aperture area. This is because of high requirement for heating in Boston with significantly more heating degree-days than Miami. In Miami, there is heating coil energy use in both heating and cooling seasons. The reason for having gas use for the furnace even in cooling season is due to the heating required for the dehumidification process in the HVAC loop.

In square skylights in Boston and Miami, the annual cooling energy follows a general trend. The annual cooling energy reduces first when square skylights are created in the roof because of the decrease in internal loads generated by fewer electric lights. At square apertures larger than 3.5% AFR, the annual cooling load increases, the reason is due to the increase in solar energy transmitted to the space. As figure 36 shows, the solar energy transmitted to the space is significantly increased when the aperture size is increased from 2% AFR to 5.5% AFR.
Figure 34 Monthly heating coil gas consumption [kBtu] in square skylights, Boston and Miami

Figure 35 Monthly cooling coil electricity [kBtu] in square skylights, Boston and Miami
Linear Apertures: Heating fuel consumption [kBtu] and cooling coil electric consumption [kBtu] are shown in Boston and Miami in figures 37 and 38 for linear apertures with different AFRs in Boston and Miami. In figure 37, monthly energy consumption of gas furnace is plotted for various roof aperture areas for linear skylights. Similar to square skylights, heating gas consumption increases in linear skylights as the aperture area increases. Effects of curbs and edges in increasing the U-value of the glazing assembly are more significant in linear skylights than square skylights with the same area. In addition, in this study, the surface area of linear apertures were more than the surface area of square apertures, therefore, larger heat loss occurred in spaces with linear apertures, resulting in higher gas heating energy requirement in those spaces rather than spaces with square skylights.

Cooling energy (figure 38) is more sensitive to variations in aperture area in Miami than Boston. In other words, cooling energy increased more significantly in Miami than Boston when the size of linear apertures increased. The reason is due to higher cooling degree-days in Miami compared to Boston. In Miami, cooling energy is required for all months of a year, as opposed to Boston, where cooling is required only from May to September. The reason is the higher solar energy transmitted to the space in cooling season in Miami than Boston. Figure 39 compares the solar energy transmitted to the space in linear apertures in Boston and Miami.

Comparing square and linear apertures, the zone transmitted solar energy is higher in linear apertures than square apertures because of having larger surface area of glazing. That fact contributes to higher cooling electric energy requirement in cooling season in linear apertures than square apertures (compare figures 36 and 39). The highest solar transmitted transmitted to the space reaches 900 kBtu in July in linear apertures with 10% AFR, which is 1.8 times the highest solar energy transmitted to the space in square skylights with 5.5%.
Figure 37 Monthly heating coil gas consumption [kBtu] in linear skylights, Boston and Miami

Figure 38 Monthly cooling coil electricity consumption [kBtu] in linear skylights, Boston and Miami
5.2.2.2. Vertical Apertures

*Vertical Apertures Facing North and South*

*Single Monitors:* Heating fuel consumption [kBtu] and cooling coil electric consumption [kBtu] is shown for single monitors with different AFRs in Boston and Miami in figures 40 and 41. The base case is shown to compare spaces with vertical apertures to the same space with no apertures on the roof. Single roof monitors are designed with 2’ light-wells. The purpose was to select the optimum Aperture-to-Floor-Area Ratio (AFR) which admits substantial sunlight and solar radiation during the heating season and which satisfies most of the summertime illumination needs without overloading the building.

In figure 40, the monthly energy consumption of the gas furnace is plotted for various roof aperture areas, for roof monitors. With adding roof monitors, heating fuel consumption increases significantly from the base case, because of increased conductive losses associated with adding glazing to the roof and the replacement of electric light with sunlight of lower heat content. As the area of apertures increases from 15% to 25%, heating fuel consumption increases at a lower rate. The reason is that solar gains compensate the combined effect of reduced heat from the electric lights and increased conductive losses associated with increased glazing area.
In Miami, there is heating coil energy use in both heating and cooling seasons. The reason for having gas use for furnace even in cooling season is that the HVAC loop requires heating for dehumidification process in Miami.

In Miami, cooling coil consumption (figure 41) is more sensitive than heating fuel consumption (figure 40) to variations in the aperture area. This is because of higher cooling degree-days in Miami compared to Boston and higher requirement for cooling when larger solar heat gain is received through larger area of glazing. In both cities, as the area of vertical glazing increases, the cooling coil electric use increases in cooling season.

Figure 40 Monthly heating coil gas consumption [kBtu] in single roof monitors, Boston and Miami
Double Monitors: Figure 42 compares single and double monitors in terms of heating energy requirement in units of kBtu in Boston. The most crucial disparity between single and double monitors is the average U-value of the glazing assemblies. The average U-values of glazing assembly proportionally increases in double monitors as the ratio of frame area to glazing area increases. As table 7 in chapter 4.2.2.2 illustrated, the average U-value of assembly in double monitors with 20% AFR is 0.56 [Btu/hr.ft².F], whereas, this value is 0.42 [Btu/hr.ft².F] in single monitors with the same AFR. This fact contributes to higher gas consumption for heating in double monitors than single monitors in Boston (figure 42).

In addition, double monitors receive less solar energy than single monitors do with the same AFR (figure 43). The reason is attributable to shadowing effect that roof monitors have on each other and larger rejection of solar rays by overhangs, which cover larger proportion of the glazing area in double monitors compared to single monitors. As a result, in Boston, all cases of double monitors with 15%, 20%, and 25% contribute to larger heating energy requirement than single monitors as figure 42 illustrates.
However, in Miami, difference between single and double monitors in terms of heating energy requirement is minor due to lower temperature differences between outside and inside during the
heating season and less conductive heat transfer through the glazing. Figure 44 compares single and double monitors in terms of cooling energy requirement in units of kBtu in Miami. Having higher U-values, the glazing assemblies in double monitors contribute to slightly higher heat transfer in cooling season than the glazing assemblies in single monitors do. Particularly, smaller double monitors (15% AFR) have higher electric energy use than single monitors with the same AFR for cooling in summertime. Effects of frames and edges on increasing the U-values of the glazing assemblies are higher in smaller glazing areas. With 15% AFR aperture area, the single monitor glazing assembly has U-value of 0.46 [kBtu/hr.Ft².F], whereas, the double monitor glazing assembly has U-value of 0.66 [kBtu/hr.Ft².F]. The significant difference between the U-values contributes to higher cooling energy use in double monitors with 15% than single monitors with the same glazing area (figure 44).

![Figure 44 Monthly cooling coil electric consumption [kBtu] in single and double roof monitors in Miami](image)

**Figure 44 Monthly cooling coil electric consumption [kBtu] in single and double roof monitors in Miami**

**Vertical Apertures Facing East and West**

**Single Monitor:** Figures 45 and 46 compare single roof monitors facing north and south with the single roof monitors facing east and west in Boston. Roof monitors have the same aperture area (20% AFR) in both cases.
Figure 45 shows that furnace gas consumption for heating is higher in heating season for spaces with roof monitors facing east and west. To benefit from solar heat gain during the heating season, south orientation is more appropriate because it receives solar energy for most hours of a day. In wintertime, daylight starts at southeast direction and ends at southwest direction with lower altitude angle, therefore, solar heat gain from vertical east and west facing apertures is lower than the vertical south facing apertures. Figure 47 shows lower zone transmitted solar energy during heating season for the roof monitors facing east-west compared to the roof monitors facing north-south in Boston.

Cooling coil electric consumption (figure 46) is higher in both cities when the vertical roof monitors are oriented towards east and west. Beam sunlight received in early hours and late hours of a day during summertime generates excessive solar heat gain in spaces with roof monitors facing east and west. Roof monitors facing north and south do not receive any beam sunlight. North facing apertures receive only diffuse daylight and overhangs reject beam sunlight from south facing apertures during the summer. As a result, zone transmitted solar energy is much higher in cooling season in spaces with vertical roof monitors facing east and west compared to the monitors oriented towards north and south (figure 47).
Figure 46 Monthly cooling coil electric consumption [kBtu] in single roof monitors with two different orientations in Boston and Miami.

Figure 47 Monthly zone solar transmitted energy in single roof monitor facing north-south and east-west in Boston.
5.2.3. Energy Use Intensity
5.2.3.1. Horizontal Apertures
In figures 48 and 49, energy use per unit of floor area per year EUI [kBtu/ft\(^2\)/yr] is categorized by type of energy consumption: equipment, fan, lighting, cooling, heating and humidifier in order to understand contribution of each category separately. The most potential saving by the use of horizontal apertures occurred for electric lighting energy consumption in both Boston and Miami. Horizontal apertures create higher potentials for whole-building energy saving in Miami than Boston due to better daylighting performance and lower heat loss through glazing in Miami.

Results show a general trend in all cases. At small AFRs, the energy consumption falls with increasing glazing area, because of the decrease in both lighting electricity and cooling electricity consumption. At larger AFRs, EUI rises slightly as increasing heating gas and cooling electricity negates the benefits in decreasing lighting electricity consumption.

For square apertures, the most energy efficiency occurs at 2% in Boston and 3.5% in Miami. The effectiveness of small area of glazing is a result of the extreme intensity of sunlight compared to the illumination level required in an office building.

In Boston, even the most energy efficient square aperture with 2% AFR requires significant heating energy to compensate the heat loss through the apertures. But reduction in electric lighting, 3.41 [kBtu/ft\(^2\)/yr], is higher than the increase in heating energy consumption, 2.9 [kBtu/ft\(^2\)/yr] from the base case. At larger skylights than 2% AFR, increase in furnace gas consumption negates the benefits of lighting electricity reduction.

In Miami, the benefits of electric use reduction is more significant than the changes in heating and cooling energy use up to an optimum AFR (3.5%). As the aperture area increases more than the optimum AFR, increase in cooling energy consumption overcomes the benefits of daylighting.
Linear Apertures: For linear skylights, EUI increases by introducing the daylighting apertures because of having larger areas than the square apertures (figures 50 and 51). The most energy efficiency occurs at the smallest aperture area (5.5% AFR) in both Boston and Miami due to less heat transfer between inside and outside.
5.2.3.2. Vertical Apertures

**Vertical Apertures Facing North and South**

In figures 52 and 53, energy use per unit of floor area per year EUI [kBtu/ft²/yr] is categorized by type of energy consumption: equipment, fan, lighting, cooling, heating and humidifier in order to understand the contribution of each category separately.

Results show the most potential saving by the use of horizontal apertures occurred for electric lighting energy consumption in both Boston and Miami. Furthermore, results show that in both Boston and Miami, the lowest energy use for spaces with roof monitors occurs at the lowest aperture area somewhere around 15% AFR. In addition, vertical roof apertures create higher potentials for whole-
building energy saving in Miami than Boston due to better daylighting performance and lower heat loss through glazing in Miami.

In figure 52, results from Boston show that adding vertical apertures to the base case increases the annual energy use per square unit of area. The reason is that heat loss through the apertures is so high that the benefits of reduced electric lighting and the benefits of solar heat gain through the glazing in heating season become negligible. Increasing the size of aperture requires higher heating gas consumption to compensate for more heat loss. Large heating energy requirement in Boston is associated with high heating degree-days created as a result of large hourly temperature differences between inside and outside during the heating season.

However, in Miami (figure 53), the energy consumption falls sharply with increasing glazing area, because of the decrease in lighting electricity. At smaller apertures, energy use for heating and cooling slightly increased in Miami, however, the benefit of electric lighting reduction is more significant, which creates a net reduction in whole-building energy use. At 25% AFR, roof monitors have almost no energy savings because of excessive solar heat gain negates the benefits of daylighting.

Figure 52 EUI in the base case and the zone with single and double roof monitors in Boston
In general, single monitors have lower energy use than double roof monitors do with the same AFR in both cities; however, difference between single and double roof monitors are more significant in Boston than Miami because of the aforementioned reasons about heat loss and heating energy requirement in Boston. Figure 54 summarizes the results from studying EUIs in roof monitors in two cities.
**Vertical Apertures Facing East and West**

In figures 55 and 56, energy use per unit of floor area per year EUI \([\text{kBtu/ft}^2/\text{yr}]\) is compared between the roof monitors facing north-south and the roof monitors facing east-west. EUI is categorized by type of energy consumption in these figures. In both single and double roof monitors in both cities, facing east-west requires higher heating and cooling energy use than facing north-south as explained in section 5.2.2.2.

*Figure 55 EUI in the zones with single and double roof monitors facing north-south and east-west in Boston*
5.3. BUILDING OPERATION COSTS

5.3.1. Horizontal Apertures

Figures 57 to 60 show the annual operating costs for energy as a function of Aperture to Floor Area Ratio (AFR) in modules (900 ft² / 83.6 m² floor area) with both square and linear horizontal roof apertures in Boston and Miami. The operation costs are calculated based on the local cost for electricity and gas in Boston and Miami. Contribution of each type of energy consumption to the total cost is shown in these figures. In addition, the total savings associated with the area of apertures are depicted. The cost per unit of energy at the site is higher for electricity than it is for gas. As a result, the variations in electricity as a function of AFR are more significant from an energy economics point of view.

In Boston, for commercial buildings, the price of electricity includes $8.14 monthly fee plus a price per kWh of electric energy, which differs on a monthly basis (NSTAR). In Oct-May, electricity costs $0.0548 per kWh and during June-Sep it costs $0.0828 per kWh. Gas price in Boston is $0.5732 per therm. In Miami, electricity costs $0.0469 per kWh for commercial buildings (FLP). Gas price for commercial buildings, which use 0-2000 annual therms, includes a monthly fee of $25 and $0.33894
per therm. In calculation of building operation costs, all the monthly charges were excluded because they included maintenance fees and they generated disproportional relations between energy and costs.

Benefits of skylights are higher in Miami, because of generally warm and sunny character of Miami and also lower operation costs in this city compared to Boston. For cold climates such as Boston, more stringent U-values are required to increase performance of skylights. However, using a triple glazed skylight with highly insulated frame will increase the cost of skylights.

In both locations, costs decrease rapidly with increasing aperture area, up to optimum aperture areas, which are 3.5% AFR in square apertures and 5.5% in linear apertures. Reductions in lighting electricity consumption and cooling electricity consumption contribute to these utility cost decreases (see figures 16 and 17 for electric lighting energy and figure 35 for electric cooling energy). Beyond an optimum aperture area, increases in heating and cooling energy exceed the decreases in lighting electricity, and the costs increase with increasing aperture area.

![Operation Costs by Category of Energy Use](image)

Figure 57 Operation cost in square skylights in Boston
Operation Costs by Category of Energy Use
[$/yr per 900 ft² or 83.6 m² module]

Miami
Square Apertures with Integrated Beveled Light Wells and Dimming Control

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Figure 58 Operation cost in square skylights in Miami

Operation Costs by Category of Energy Use
[$/yr per 900 ft² or 83.6 m² module]

Boston
Linear Apertures with Integrated Beveled Light Wells and Dimming Control

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Figure 59 Operation cost in linear skylights in Boston
Figure 61 compares square and linear horizontal apertures in terms of operating cost for energy in modules with different AFRs in Boston and Miami. The most potential cost benefits are achieved at 3-3.5% AFR for square skylights at both climates. For linear apertures, the highest level of saving occurs for 5.5% AFR in Miami and Boston. Skylights with optimum aperture area (3.5% square skylights) can save $0.08 per ft² ($0.89 per m²) of floor area per year in Boston and $0.09 per ft² ($0.98 per m²) of floor area per year in Miami. Results show that an economically optimum skylight saves 72%-88% of annual lighting energy consumption in Boston and Miami respectively. Savings are less in linear apertures because of negative effects of increasing the aperture size. Using an oversized aperture (larger than 10% AFR) does not contribute to any savings in both climates and in fact, operation costs rise from the base case in this condition.
Figure 61 Building operation costs [$ per module of 900 sqft or 83.6 m²] in Boston and Miami for square and linear skylights

5.3.2. Vertical apertures

*Vertical Apertures Facing North and South*

Figures 62 and 73 show the annual operating cost for energy as a function of Aperture to Floor Area Ratio (AFR) in modules (900 ft²/83.6 m² floor area) with single and double roof monitors in Boston and Miami. The operation costs are calculated based on the local cost for electricity and gas in Boston and Miami. Contribution of each type of energy consumption to the total cost is shown in these figures. In addition, the total savings associated with the area of apertures are depicted. The cost per unit of energy at the site is higher for electricity than it is for gas. As a result, the variations in electricity as a function of AFR are more significant from an energy economics point of view. The cost of electricity and gas in Boston and Miami is explained in 5.3.2.
In both locations, costs decrease rapidly with introducing vertical apertures at 15% AFR due to reductions in lighting electricity consumption (see figures 17 and 18). Beyond an optimum aperture area, increases in heating fuel consumption in Boston and rises in cooling electricity in Miami exceed the decreases in lighting electricity. As a result, the costs increase with increasing aperture area.

Figure 64 compares vertical apertures in terms of operating cost for energy in modules with different AFRs in Boston and Miami. The most significant observation is the striking similarity of the two cost curves. Benefits of roof monitors are higher in warmer climates such as Miami with less heating degree-days. As expected, the Miami curves reach the minimum operation cost, which reflects the
generally warm and sunny character of Miami and also lower operation costs in this city compared to Boston. For cold climates such as Boston, more stringent U-values are required to increase performance of roof monitors. However, using a triple glazed window with highly insulated frame will increase the cost of roof monitors.

The most potential cost benefits are achieved at 15% AFR for single roof monitors at both climates. Roof monitors with optimum aperture area can save $0.05 per square foot ($0.53 per m²) of floor area per year in Boston and $0.07 per square foot ($0.72 per m²) of floor area per year in Miami. Results show that an economically optimum roof monitor saves 98%-100% of annual lighting energy consumption in Boston and Miami respectively.

Figure 64 Building operation costs [$ per module of 900 sqft or 83.6 m²] in Boston and Miami for single and double roof monitors with different AFRs facing north-south

Figure 65 compares vertical apertures facing north-south to the vertical apertures facing east-west in terms of operating cost for energy in modules with 20% AFRs in Boston and Miami.
5.4. CONCLUSIONS AND DISCUSSION

From an illumination point of view, horizontal apertures tend to be more efficient in gathering useful light. Horizontal apertures in a flat roof produce higher illuminance on the floor or on a horizontal working plane than vertical aperture of the same area for three reasons:

- The openings receive light from a large area of sky
- In overcast days, sky tends to be brightest at the zenith
- The apertures face directly down towards the work plane
- There is nearly perpendicular angle of incidence in horizontal apertures

Therefore, to gather adequate amount of illumination, less glazing is required on the horizontal as compared to the vertical.

From a heating point of view, vertical apertures facing south are preferred because they face toward the winter sun, the collection of which helps to offset some of the heating loads.

From a heating point of view, horizontal apertures are preferred because less glazing area is required and this is generally a good thing, since glazing has a much higher U value than opaque insulated roof.
From a cooling point of view, aperture facing north and south are preferred because they avoid the midday summer sun.

Figure 54 compares horizontal and vertical roof apertures investigated in this study in terms of building operation costs. Finally, regarding the results from building operation energy costs, the maximum potential energy savings occurred in spaces with skylights with minimal aperture areas (3-3.5\% AFR). Horizontal apertures in a flat roof produce higher illuminance on the floor or on a horizontal working plane than vertical monitors of the same area. As a result, the area of required glazing could be minimized in skylights, thereby minimizing thermal effects of conductive gains and losses through the building envelope. In addition, the capital cost of the glazing will be minimized when glazing area is minimized.

Daylighting systems that provide uniform illumination are more energy efficient specifically during the cooling season. Uniform daylight illumination satisfies lighting requirement in a space without aggravating the cooling loads. Design of skylights with integrated and beveled light-wells was a major task to achieve uniform daylighting in case of horizontal apertures.

Comparing double and single roof monitors, double roof monitors provide more uniform lighting compared to single monitors, which exhibit higher maximum and lower minimum illuminance across the space. With uniform illuminance across the work plane, lighting requirements in the space are met without excess solar gains that will aggravate the cooling loads.

Double roof monitors have the disadvantage that there are more curbs and edge effects on the glass, increasing the envelope surface area and increasing the average U value for the envelope. This effect is primarily of concern during the heating season, when heat losses will be increased by the increase in UA for the envelope. For the simulations run, the problem is much larger in Boston than in Miami, because of the much larger heating load in Boston.

On balance, the single and double roof monitor configurations performed about the same from an energy operating cost point of view. This conclusion may not be completely generalizable. For this study, the target illuminance was very low (300 lux). As a consequence, even accounting for the non-uniformity of the illuminance for the single roof monitors, there was not significant thermal overloading during the cooling season. If the target illuminance level was significantly increased, we would expect an increase in cooling load associated with the non-uniform illuminance, which would favor the double monitors over the single monitor configuration.
In interpreting the results of this study, the reader should remain cognizant of the fact that the target illuminance of 300 lux on the work plane is at the very low end of what we would prescribe in office spaces; 550 lux would be more common. The expected energy benefits of the roof monitors would be substantially increased for a higher target illuminance. In a sense, this study is the worst-case scenario for assessing the potential of using daylighting from roof monitors for interior illumination in that we have accepted a very low illuminance level for the expressed purpose of reducing energy consumption through conservation. “Free” daylighting gives us the option to seek a light level that would be much more optimal from a human point of view.

The shapes of the energy costs for skylights in figure 54 were influenced by assumptions in the study: Electric charges did not include peak-power demand charges. Including peak-power demand charges will highlight benefits of daylighting because of reducing electric use at noon, which is the highest demand for cooling.

The office building was modeled with 13’ 7” (9.14 m) roof height in this study. For fixed number and area of skylights, increasing the ceiling height would result in more even illumination at task surface; thus, less dark spots are created and fewer light fixtures are required in the space. In fact, ceiling height has a major impact upon the economics of roof daylighting systems because a higher ceiling enables fewer, larger skylights to be used to achieve similar lighting levels. In that case, less heat loss would occur through the skylights and initial costs are reduced by buying fewer skylights. By lowering the ceiling height, additional skylights are required to maintain daylight uniformity, which adds to the costs and heat losses associated with curb and framing effects. Therefore, cost benefits of roof-daylighting systems will be higher in commercial and industrial buildings with higher ceilings.

In this study, diffusing glazing material with 42% visible transmittance was used for skylights. Higher visible transmittance would increase SHGC of the glazing material higher to the required level by ASHRAE 90.1-2010 (30% maximum SHGC is allowed in Miami). The advent of glazing materials that can transmit higher levels of visible light without transmitting solar heat would increase daylighting performance and cost benefits of skylights.

The electric lighting control was a dimming control that performed ideally to generate electric light in proportion to reductions in available daylight. Electric lighting controls with ON/OFF switch will use higher electric lighting and create disturbing effect while sudden changes occur in sky illumination.
such as cloudy days. However, such electric lighting systems are simpler and less expensive, and will be investigated as this study continues to evolve.

Curbs have significant impact on increasing $U$-values of skylight assemblies; therefore, reducing the negative effects of curb would facilitate additional reductions in both energy reduction and energy costs. In addition, using external shading makes it possible to reduce excessive solar heat gain and reduce cooling loads. This fact will also have impact on reducing energy consumption and operation costs in skylights.

A furnace of 80% efficiency was assumed in this study. Improving furnace efficiency would reduce the negative cost impacts of heat loss through the roof monitors.

In the final analysis, the greatest motive for introducing daylighting into a building is the life-quality issue. In the light of that fact, we should not imagine that we had done proper “economic analysis” when we have only consider the benefit of reduced energy operating cost.

![Figure 66 Building operation costs [S per module of 900 sqft or 83.6 m²] in Boston and Miami for (A) Horizontal roof apertures (B) Vertical roof apertures](image-url)
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